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CONTENTS

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THE FAILURE OF EXCHANGE BETWEEN VITAMIN B_{12r} AND RADIOACTIVE COBALT CHLORIDE

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That exchange fails to occur between vitamin B_{12} and inorganic cobalt in the form of $Co^{60}(NH_3)_6Cl_3$ and $Co^{60}Cl_2$ was reported by Fantes et al. (1). The failure of the B_{12}-bivalent cobalt exchange to occur has recently been confirmed (2, 3) under a variety of conditions of acidity and at times up to three months. Nor did exchange occur when the vitamin in solution with $Co^{60}SO_4$ was irradiated with white light which is known to cause the release of the cyanide group from vitamin B_{12} (3). The cobalt in B_{12} is in the trivalent state as shown by magnetic susceptibility measurements (4). The catalytic hydrogenation of B_{12} over platinum yields a brown material which on exposure to air yields B_{12a} (5). The brown material, which has been designated B_{12r}, has been shown to contain bivalent cobalt (6). The ammines of bivalent cobalt are in general much less stable than those of trivalent cobalt so that it appeared possible that exchange might occur between B_{12r} and $Co^{60}Cl_2$. Exchange should be more likely under such conditions also because the metal is in the same valence state in each reactant.

We have found that this exchange does not occur and report the details of the experiment herewith. Cobalt is indeed tied into the B_{12} molecule with extraordinary tightness.

EXPERIMENTAL WORK

In 10 ml of 0.1 N potassium sulfate was placed 100 mg of crystalline B_{12} (Squibb) and 100 mg of platinum oxide catalyst. Hydrogen was bubbled through the solution for 10 hours. The platinum was filtered off and the black solution transferred to a cell containing 5.0 ml of standard $Co^{60}Cl_2$ solution, the operations being carried out without contact with air. A slow stream of hydrogen was passed through the solution for 60.5 hours, the solution being stirred magnetically during this time. The solution was than exposed to air and treated with 0.2 g of sodium cyanide. The solution was then saturated with ammonium sulfate and extracted with butanol five times. Only a little B_{12} color remained in the water layer. The butanol layer was washed repeatedly with water saturated with ammonium sulfate. The radioactivity transferred to the ammonium sulfate washes dropped rapidly but was high and constant in the fifth and sixth washes. An auxiliary experiment with $Co^{60}Cl_2$ showed that inorganic cobalt (cobalt chloride and potassium cobalticyanide) passing into butanol was extracted quantitatively into the aqueous layer by two such washes with saturated ammonium sulfate solution. The B_{12} was then extracted from the butanol by washing six times with 50 ml portions of water.

The $Co^{60}Cl_2$ solution used was obtained from the Oak Ridge National Laboratory through the A.E.C. Isotope Division. The $Co^{60}Cl_2$ standard was prepared by diluting 100 μl of the original source to 25.0 ml. The activity of the standard was measured by diluting 100 μl to 10.0 ml and evaporating 100 μl of the solution on a watch glass and counting with an end window Geiger-Müller tube (2.2 mg/cm²). After correction for background the 5.0 ml of the standard $Co^{60}Cl_2$ solution taken was calculated to have an activity of 1.45×10^7 c/m. Suitable aliquots of the residual water solution, the ammonium sulfate wash, and the final water solution were counted in a similar manner. About 88 per cent of the activity remained in the original water solution, about 2 per cent passed into the colorless ammonium sulfate wash, and 6.4 per cent passed into the colored, aqueous solution.

The colored, aqueous solution (containing 6.4 per cent of the original activity) was passed through a column of IRC50 at pH 7. The column was washed with a large volume of water. Of the activity, 78 per cent came through the column immediately as a colorless solution; the rest of the activity remained at the top of the column with the adsorbed colored material. The wash water came through inactive.

The colored material on the column was eluted with 60 per cent isopropanol 1.0 N in sulfuric acid. This eluate was neutralized with sodium hydroxide and subjected to vacuum distillation. After the volume had been reduced to 100 ml methyl alcohol was added and the salt so precipitated was filtered off. Vacuum distillation and precipitation were twice repeated, progressively decreasing the volume. The solution was then treated with a little cyanide, methyl alcohol was added, the solution filtered and again evaporated to small volume. This final solution, orange in color, contained about 22 per cent of the total radioactivity of the butanol extract (1.4 per cent of the original). The absorption spectrum showed a peak at 355 mμ but was quite different from the absorption spectra of B_{12} or B_{12a} in the visible having a broad peak at 440 to 460 mμ. No change in absorption spectrum resulted on passing the solution through a column of IR120 in acid form. The solution was inactive microbiologically.

The colorless eluate from the IRC50 solumn was freeze dried. A white, fluffy solid, mostly ammonium sulfate, was obtained which was highly radioactive but inactive biologically. No attempt was made to further characterize the radioactive cobalt compound.

DISCUSSION AND CONCLUSIONS

It is apparent that vitamin B_{12} containing radioactive cobalt cannot be prepared by exchange between B_{12r} and $Co^{60}Cl_2$. The colored, B_{12}-like and radioactive material obtained might possibly be construed as having resulted from exchange between B_{12} and $Co^{60}Cl_2$ followed by sufficient destruction of the B_{12} by the prolonged hydrogenation or the 1.0 N sulfuric acid used in eluting to render the material inactive biologically. In any case the specific radioactivity is so low that the process would be of no interest, even if conditions could be found to preserve the bioactivity.

The formation of the colorless, radioactive cobalt compound having solubility characteristics much like those of B_{12} indicates that on exhaustive hydrogenation, the chromophore of B_{12} is destroyed and that in the new compound formed the cobalt is not so tightly bound.

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CHEMOAUTOTROPHIC FIXATION OF CARBON DIOXIDE BY THIOBACILLUS THIOOXIDANS[1]

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The mechanism of carbon dioxide fixation by chemoautotrophs has been studied only recently by several workers.

In 1955 Santer and Vishniac reported the carboxylation of ribulose diphosphate by the cell-free extracts of *Thiobacillus thioparus* (1). In the same year Trudinger also reported the same carboxylation reaction by extracts of *Thiobacillus denitrificans* (2) and the next year he further extended his work with extracts and concluded that this organism was capable of synthesizing carbohydrate from carbon dioxide by a cyclic mechanism similar to that of photosynthesis (3).

Aubert, Milhaud, and Millet, on the other hand, worked on whole cells and published their results on the short-time exposure experiments of *T. denitrificans* using radioactive carbon dioxide (4). They identified labeled compounds such as 3-phosphoglyceric acid, hexose phosphates, sedoheptulose phosphate, ribulose diphosphate, and aspartic acid, and concluded the identity of the mechanism of carbon dioxide fixation by photosynthesis and chemoautotrophy.

In a study of the metabolism of *Thiobacillus thiooxidans*, an acid-loving, aerobic chemoautotroph, cells oxidizing sulfur have been exposed to $C^{14}O_2$ for various periods and the radioactive products determined. Some of the radioactive compounds were degraded in order to determine the position of radioactive atoms in the molecules.

MATERIALS AND METHODS

Thiobacillus thiooxidans No. 8085 was obtained from the American Type Culture Collection. The organism was grown in a Fernbach flask containing 700 ml of Starkey's medium (5), with the composition shown in Table 1. Seven grams of powdered sulfur were spread on the surface as a source of energy. The flask was incubated for 7 days at 30°C. Sulfur was removed by filtration through Whatman No. 1 filter paper under vacuum. The cells were collected by centrifugation and resuspended in 30 ml of medium B with 1.5 g of sulfur and were shaken for 3.5 hours. Tween 80, a wetting agent, assists in the dispersion of sulfur particles throughout the medium and was shown by Starkey *et al.* to increase the rate of sulfur oxidation during growth (6). After incubation, the active sulfur-oxidizing cells together with sulfur particles were harvested again by centrifugation. They were finally suspended in 30 ml of medium B, adjusted to pH 2.0 with sulfuric acid and were then used.

[1]Supported in part by the U.S. Public Health Institute.

Table 1. Media

	A. Starkey's Medium	B. Suspending Medium
$(NH_4)_2SO_4$	0.3 g	0.3 g
KH_2PO_4	3.5 g	3.5 g
$MgSO_4 \cdot 7H_2O$	0.5 g	0.5 g
$CaCl_2$	0.25 g	--
$CaSO_4 \cdot 2H_2O$	--	0.2 g
$FeSO_4 \cdot 7H_2O$	0.02 g	0.02 g
Tween 80	--	0.05 g
Distilled water	1000 ml	1000 ml
pH	4.5	4.5

A specially designed flask had a side arm to hold radioactive sodium bicarbonate and a hole at the bottom through which a stopcock led to a flask containing 500 ml of boiling water. The cell-sulfur suspension was introduced into the flask together with 1 ml of 0.01 N $NaHCO_3$ (specific activity of 5×10^7 c.p.m./ml) in the side arm, and then the flask was evacuated and refilled with CO_2-free air at atmospheric pressure. The reaction was started by tipping the solution of radioactive bicarbonate into the cell suspension. The system was agitated by a magnetic stirrer. After a fixed time the reaction mixture was flushed into the boiling water in the connecting flask and boiled for 10 minutes to kill the cells. Nitrogen gas was psssed through the boiling water during this period to remove the residual $C^{14}O_2$.

The reaction mixture was filtered through Whatman No. 1 filter paper to remove sulfur particles and the filtrate was concentrated and dried under vacuum at 30°C. Thirty ml of 80 per cent ethanol extracted most of the radioactivity from the concentrated residue. The solid material, separated by centrifugation, was further extracted with 10 ml of 80 per cent ethanol. The ethanol fractions were combined and subjected to fractionation by passing through cationic and anionic ion exchange columns in series. Two Amberlite resins, IR-120 and IR-4B, were used as H-form and OH-form respectively. The elution was carried out with 4 N NH_4OH followed by water. Three fractions, neutral, cationic, and anionic, were concentrated separately under vacuum and a fraction of each was subjected to two-dimensional paper chromatography.

Identification of radioactive compounds.

The identification was carried out by two-dimensional paper chromatography and radioautography. Eighty per cent phenol and BABW (butanol:butyric acid:water = 2:2:1) (7) were used as the solvents. Whatman No. 1 filter paper was used throughout the experiment. Radioactive compounds were detected by superimposing a sheet of Kodak No-Screen Medical X-ray film on the chromatogram. Each spot was cut and the radioactivity was directly counted under a mica-window Geiger-Müller tube. The compound on the spot was transferred to the origin of a new chromatogram by the method of Gregory (8) and developed with an additional selected solvent simultaneously with authentic compounds. At least three different solvent systems were used before reaching a final decision as to identity. As the last step, the unknown compound was mixed with an authentic compound and was compared chromatographically. The identity of position and shape of a spot on a radiogram and of that on a chromatogram revealed by a color reaction was considered as proof of identity of the two compounds. Phosphorylated compounds were treated with 0.1 per cent solution of Schwartz's Polidase and the hydrolyzed compounds were further identified by paper chromatography.

Radioactivity.

Radioactivity was measured with a lead-shielded end-window (mica) Geiger-Müller tube. Samples for degradation were determined on ground glass planchets. $BaCO_3$ from degraded compounds was collected by filtration on a Whatman No. 42 filter-paper disc with a known area. The radioactivity counted on this filter-paper was corrected for self-absorption as well as the paper glass planchet effect, in order to compare the activity with that determined on a glass planchet.

Degradation of compounds.

The degradation of compounds was carried out in a specially designed flask with a side-arm, an inlet and an outlet. CO_2-free nitrogen gas was admitted through an inlet and served to agitate the reaction mixtures. The gas also served for the transportation of CO_2, formed by the degradation, through an outlet to a CO_2 trap containing a solution of 0.2 N NaOH (CO_2-free). Carrier compounds were always added to the radioactive compounds in order to determine the yields of $BaCO_3$. Glyceric acid was degraded by the method of Aronoff (7) with periodic acid and perchloratoceric acid. Radioactivities of the carboxyl carbon atom and the α-carbon atom were determined. The two carboxyl groups of aspartic acid, α-carboxyl group of glutamic acid, and the carboxyl group of serine was decarboxylated with ninhydrin according to Vernon and Aronoff (9). The ninhydrin reaction was carried out in a citrate buffer of pH 2.5. The α-carboxyl carbon atom of aspartic acid was obtained after conversion to malic acid with HONO and the Von Pechman oxidation of the isolated malic acid (10). The gamma-carboxyl group of glutamic acid was released according to Schmidt as modified by Phares (11) with NaN_3 and H_2SO_4.

EXPERIMENTAL

Identification of labeled compounds.

Three experiments were run with time durations of three minutes, ten seconds, and two seconds. The identity of the radioactive compounds and the distribution of radioactivity among the compounds are shown in Table 2.

Table 2. Identification of radioactive compounds.

Compound identified	Distribution of Activity* 3 min. fixation (%)	10 sec. fixation (%)	2 sec. fixation (%)
Amino Acids			
Aspartic acid	4	24	8
Glutamic acid	8	3	2
Serine	5	5	2
Alanine	1	$\not 1$	
Threonine	$\not 1$		
Valine	3		
Leucine	$\not 1$		
Isoleucine	$\not 1$		
Phosphate Esters			
Phosphoglyceric acid	3	33	80
Glucose phosphates	36	27	
Sugars			
Glucose	10	2	
Fructose	1	$\not 1$	
Mannose	$\not 1$		
Rhamnose	1		
Ribose		$\not 1$	
Ribulose		2	
Dihydroxyacetone	$\not 1$	$\not 1$	
Organic Acids			
Glyceric acid	6	3	
Malic acid		3	
Tartaric acid	15		
Unidentified	12		

* $\not 1$ = Activity less than 1 per cent.

All the amino acids were identified from the cationic fractions and gave positive reactions with ninhydrin. Aspartic acid is by far the most rapidly labeled amino acid followed by glutamic acid and serine. Other common amino acids, e.g., alanine, threonine, valine, leucine, isoleucine, were more slowly labeled. The chromatogram of the cationic fraction from a three-minute fixation experiment gave a ninhydrin positive pattern almost identical to its radiogram pattern, indicating the incorporation of C^{14} in all the free amino acids during this period. A few radioactive spots on the chromatogram which did not correspond to any of the ninhydrin positive spots or any known amino acids were hydrolyzed with 6 N HCl for five hours at 120°C. The first spot gave rise to alanine and threonine, the second to alanine and aspartic acid, and the third spot to glutamic acid. The above evidence indicates that those spots were probably peptides and that the radioactivity was already incorporated in peptides in three-minute $C^{14}O_2$ fixation. There was no formation of peptides in ten seconds or two seconds.

Phosphate esters, sugars, and organic acids were identified in anionic and neutral fractions. It is apparent that phosphoglyceric acid is the most rapidly labeled compound. Thus in two-second fixation 80 per cent of the total activity fixed was found in phosphoglyceric acid. When the cells were exposed to $C^{14}O_2$ for a longer period, the activity appeared in glucose phosphates, some sugars, and organic acids. Glyceric acid and some of the sugars probably were derived from the phosphate esters. The presence of common hexoses, pentoses, and dihydroxyacetone suggests the similarity of the carbohydrate metabolism of this organism to that of other organisms. On the other hand, the absence of sedoheptulose among the products of fixation and the very low activity found in fructose distinguish this organism from photosynthetic organisms or *T. denitrificans* (4). It is possible, however, that these compounds might not have accumulated in detectable quantities. Among the organic acids of the tricarboxylic acid cycle, malic acid was the only one detected, probably due to their rapid incorporation into amino acids. The role of tartaric acid in the metabolism of this organism is not known. The unidentified compound in the three-minute fixation product is possibly a gluconic acid derivative according to its chromatographic behavior. These two compounds, however, were not found in shorter time exposure experiments and therefore are not important as first intermediates of carbon dioxide fixation.

Degradation of radioactive compounds.

Several radioactive compounds were degraded and the location of radioactivity in the molecules was determined (Table 3). Phosphoglyceric acid from two-second and ten-second fixation products was hydrolyzed with polidase, and glyceric acid was isolated by paper chromatography. Likewise aspartic acid, serine, and glutamic acid were isolated from ten-second and three-minute fixation products by paper chromatography. The radioactivity of phosphoglyceric acid was located mostly in its carboxyl group and more so in two-second than in ten-second fixation. Thus 89 per cent of the activity of phosphoglyceric acid from the two-second fixation experiment was found in its carboxyl carbon atom. This result is in agreement with those of photosynthetic carbon

Table 3. Degradation of radioactive compounds.

Compound		2 sec. (%)	10 sec. (%)	3 min. (%)
Glyceric acid	COOH ---	89	67	
	HCOH ---	7	16	
	CH_2OH---	4	18	
Serine	COOH ---	--	74	49
	$HCNH_2$			
	CH_2OH			
Aspartic acid	COOH ---	--	22	
	$HCNH_2$			
	CH_2			74 (both carboxyl groups)
	COOH ---	--	78	
Glutamic acid	COOH ---	--	63	38
	$HCNH_2$			
	CH_2			
	CH_2			
	COOH ---	--	13	5

dioxide fixation and indicates the presence of a common mechanism, i.e., the carboxylation of ribulose diphosphate. The carboxyl carbon of serine was also rapidly labeled as expected from a scheme in which phosphoglyceric acid is a precursor in its biosynthesis (12).

The degradation of aspartic acid and glutamic acid revealed the preferential labeling of β-carboxyl group of aspartic acid and α-carboxyl group of glutamic acid. This result can be best explained by the formation of β-carboxyl labeled oxalacetic acid and its oxidation through the Krebs cycle to α-ketoglutaric acid. The transamination of these keto-acids will form β-carboxyl labeled aspartic acid and α-carboxyl labeled glutamic acid. It is not surprising that radioactive oxalacetic acid was not detected among the fixation products when its lability is considered.

DISCUSSION

The formation of phosphoglyceric acid from pentose phosphates and carbon dioxide, and the formation of oxalacetic acid from phosphoenol-pyruvic acid and carbon dioxide by the cell-free extract of Thiobacillus thiooxidans are reported elsewhere (13, 14). The enzyme systems necessary for the recycling of pentose phosphates and the conversion of phosphoglyceric acid to hexose phosphate are also reported (13). The results obtained in this paper indicate the occurrence of these two carboxylation systems in the whole cells of T. thiooxidans. A proposed scheme of carbon dioxide fixation by this organism is shown in Fig. 1.

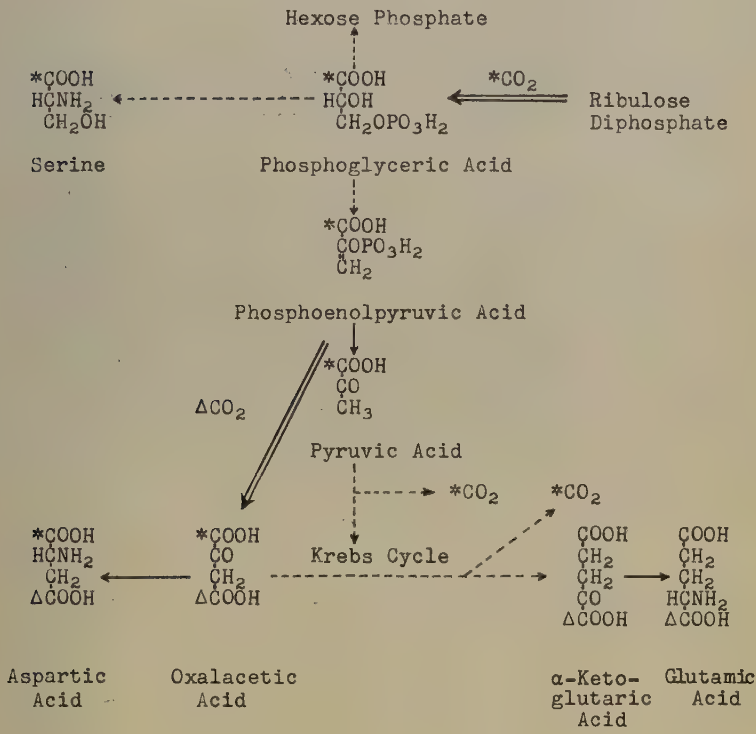

Fig. 1. Proposed scheme of carbon dioxide fixation by <u>Thiobacillus thiooxidans</u>.

In the presence of $C^{14}O_2$ ribulose diphosphate will be carboxylated to form carboxyl-labeled phosphoglyceric acid, which in turn will be converted to radioactive glucose phosphates and other sugars and also carboxyl-labeled serine. On the other hand, phosphoenolpyruvate will be carboxylated to form β-carboxyl labeled oxalacetic acid. The α-carboxyl group of oxalacetic acid may be labeled later owing to the labeling of the carboxyl group of phosphoenolpyruvic acid. When oxalacetic acid is oxidized to α-ketoglutaric acid via the Krebs cycle, the radioactivity at the β-carboxyl group of the former acid will be found in the α-carboxyl group of the latter acid. Both keto-acids will be converted to the corresponding amino acids by transamination or ammoniation. Thus this scheme is in full agreement with the results obtained in this paper. The occurrence of other carboxylation systems in the metabolism of <u>T. thiooxidans</u> is not excluded. Apparently, however, these two systems, i.e.,

the formation of carboxyl-labeled phosphoglyceric acid and β-carboxyl labeled oxalacetic acid, predominate in the carbon dioxide fixation by this organism.

The rapid labeling of the α-carboxyl group of glutamic acid is interpreted also as indirect evidence of the presence of the Krebs cycle in this organism, although more work is necessary before making a definite conclusion.

The incorporation of radioactivity in some peptides in three-minute fixation products was interesting from two points. First, this may be related to the mechanism of protein synthesis in this organism, i.e., amino acids may go through the stage of peptides before being incorporated into protein. Further work should be done, however, before making any conclusion. Secondly, since at least one of the peptides acted exactly like proline in paper chromatography and could not be separated from it when mixed with it, this represents another case where the identification by paper chromatography of free amino acids in a natural substance requires the hydrolysis of the sample as claimed by Deane and Truter (15).

The results obtained in this paper and those of others (4) clearly indicate the similarity of photosynthesis and chemoautotrophy as far as the mechanism of carbon dioxide fixation is concerned.

SUMMARY

The cells of Thiobacillus thiooxidans oxidizing sulfur were exposed to $C^{14}O_4$ for various periods and the radioactive compounds formed were determined by paper chromatography.

In two-second fixation 80 per cent of the activity fixed was found in phosphoglyceric acid and 8 per cent in aspartic acid. When the length of duration of exposure was increased, the radioactivity appeared in glucose phosphates, sugars, organic acids, amino acids, and peptides.

Some of the labeled compounds were degraded and the location of radioactivity in the molecule was determined. The carboxyl groups of phosphoglyceric acid and serine, β-carboxyl group of aspartic acid, and α-carboxyl group of glutamic acid were found preferentially labeled in the molecules.

It is concluded that two carboxylation systems, i.e., the carboxylation of ribulose diphosphate to form phosphoglyceric acid and the carboxylation of phosphoenolpyruvate to form oxalacetate, are working in the carbon dioxide fixation by T. thiooxidans.

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SOIL ERODIBILITY AND OTHER PHYSICAL PROPERTIES OF SOME IOWA SOILS[1]

John E. Adams, Don Kirkham, and Wayne H. Scholtes[2]

INTRODUCTION

This study was originally sponsored by the Iowa State Conservation Commission to investigate the watershed erodibility of prospective artificial lake sites in Iowa. Highly erodible watersheds are not desirable locations for future lakes unless adequate control measures can be developed prior to reservoir completion. Upon discontinuance of reservoir construction by the Conservation Commission, the study was further expanded by the Iowa Agricultural Experiment Station to measure more accurately the erodibility and other physical properties of Iowa soils. This information is needed for soil conservation planning and for other purposes. The particular aspect of erosion to be studied was that of soil type. Factors such as slope of the land, length of the slope, etc., were not to be a part of the investigation. A portable artificial rainfall maker, with associated equipment, was, together with a specially designed air permeameter, to be the principal equipment used in evaluating the soils in the field. In the laboratory, measurements of soil properties related to soil erodibility were to be made. From the field and laboratory data the soils were to be classified into groups according to their erodibility so that the Browning erosion factors (10; 69, p.434) for the soil types could be obtained.

REVIEW OF LITERATURE

Factors Affecting Soil Erosion

Many studies have been made of soil erosion and the factors affecting soil erosion. Baver (5, pp. 349-386) has brought some of the more important ones together in a chapter entitled "Physical Properties of Soils in Relation to Runoff and Erosion." He stated that erosion is a function of climate, topography, vegetation, soils, and the human factor. Neal (50) gave a literature review regarding slope and rainfall characteristics in relation to runoff and erosion. Osborn (56) reviewed the existing literature on factors affecting sheet erosion. Bennett (7) presented a comprehensive literature review of studies since 1895 of raindrop characteristics and gave a discussion of raindrop splash.

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[1]Journal paper No. J-3329 of the Iowa Agricultural and Home Economics Experiment Station, Ames, Iowa. Project No. 1064.

[2]Graduate Assistant, and Professors of Agronomy (soils). The senior author is now soil scientist, Western Soil and Water Management Section, S.W.C., A.R.S., Temple, Texas.

Ekern (19) presented a comprehensive review of the literature on the kinetic energy of natural rainfall and the soil factors affecting it. He stated that the kinetic energy for natural rainfall varies from 1,000 to 100,000 times the work capacity of shallow sheets of runoff water. Ekern found that approximately 8 tons per acre of fine sand would be transported by the impact of drops from a rainfall of 4 inches per hour continuing for a 5-minute period. Nichols and Gray (53) stated that 2 inches of rain on an acre would have 194,900,000 foot-poundals or 6,000,000 foot-pounds of kinetic energy, which they calculated to be sufficient to raise a 7-inch layer of soil a height of 3 feet over an area of one acre. Mihara (46) thought that the impact of raindrops was the main cause of sheet erosion and suggested that precipitation be reported as kinetic energy rather than as amount.

Ekern (20) reported that the impact energy of rainfall was a nearly identical function of intensity and slope, and that the additive energy of shallow flow and drop impact should approximate the 1.5 power of the storm intensity. He concluded that the erosivity of storms should be proportional to the additive kinetic energy from the impact of falling rain and shallow flow of water. Borst and Woodburn (9) observed that elimination of raindrop impact, rather than reduction of overland flow velocity, was the major contribution of a mulch in reducing soil loss. Neal (50) constructed an "impactometer" to measure and automatically record the impact of falling drops of water. Laws (38) studied drop sizes varying from 1 to 5 mm in diameter and found that as the drop size increased, the infiltration rate decreased by as much as 70 per cent, and that erosion losses increased 1200 per cent.

Slope and vegetation are also important factors affecting erosion. Baver (5) considered the degree of slope to be more important than length of slope from the standpoint of erosion. Literature on the effect of slope has been reviewed by several authors (5, 50).

Baver (5) discussed the effect of vegetation upon erosion in considerable detail and classified it into several categories including, (a) the interception of rainfall by the vegetative canopy, (b) the decreasing of the velocity of runoff and the cutting action of water, and (c) root effects in increasing granulation and porosity. In 1880 Wollny [see Baver (4)] investigated the effect of plant cover upon the interception of rainfall and found that from 45 to 88 per cent of the total rainfall reached the land surface directly, depending upon the type of crop and the number of plants per unit area. Clark (12) found that the percentage of interception of rainfall varied with the intensity of the rainfall, density of foliage cover and environmental conditions. Osborn (58) presented data showing that for effective control of raindrop energy, approximately 2000 pounds per acre of short sod grasses, 3500 pounds of ordinary crops or grasses, or 6000 pounds of tall coarse crops and weeds were required.

Methods of Measuring Soil Erosion

Probably the most nearly absolute method for studying the erodibility and water intake capacity of soils is by the use of "control plots" where factors can be controlled or of watersheds of a known size or surface area. Soil and water losses from the control plots or watersheds are

measured after each rain under natural field conditions, including the effect of growing vegetation. Runoff control plots and watershed structures are expensive to install, costly to maintain, and must be operated over a long period of time to obtain the variation of natural rainfall intensities desired. For this reason a number of rainfall simulators have been developed and used to obtain infiltration, runoff, and erosion data. The use of simulated rainfall makes it possible to obtain water intake and soil erodibility data in the field over a wide range of rain intensities in a much shorter time and with considerably less expense than by the use of watersheds or runoff control plots.

A number of rainfall simulators have been constructed and used for special studies in erosion. Neal (50) used an overhead sprinkling system suspended 4 feet above the soil surface of a plot 1/1000 of an acre in area to study the effect of the degree of slope and rainfall characteristics on runoff and soil erosion. The plot consisted of a wooden tank 12 feet long, 3.63 feet wide and 2 feet deep. Borst and Woodburn (8) used the type-E apparatus to investigate the effect of the degree of slope on erosion and runoff. The apparatus was designed for use on plots 72.6 feet x 6 feet and required about five man days to assemble. A "portable rain maker and erosion study apparatus" was developed by Craddock and Pearse (14) to study the effects of important herbaceous range cover type of the Boise River watershed on runoff and erosion. This apparatus was constructed for use on plots 6.6 feet x 33 feet. Ellison and Pomerene (24) designed a rainfall simulator for a plot 5 x 6 feet, which Ellison used in most of his erosion studies. Basu and Puranik (2) constructed a laboratory rainfall simulator, similar to the type devised by Ellison and Pomerene, to be used in a study of the susceptibility of Indian soils to erosion. This apparatus was designed for use on a fixed plot or soil tray 9 x 3 feet. Osborn (55, 56) described in detail a "mobile raindrop applicator" which was constructed by the Soil Conservation Service. The mobile raindrop applicator was designed along the basic principles as suggested by W.D. Ellison and was mounted on a one-ton truck. This apparatus delivered drops from a height of 14 feet to a small plot 12 x 18 inches. Splash erosion and surface runoff were collected by means of this apparatus. A splash collecting apparatus was developed and used by Sreenivas et al. (68) to measure soil detachment caused by artificial or natural rainfall under different soil cover conditions.

Infiltration Studies

Infiltration rates of a soil are related to soil erodibility; methods for studying infiltration can be divided into two general groups: those in which water is ponded over a small area and infiltration is equal to the water applied to maintain a small head, and those where the water is applied as a spray or simulated rainfall and the infiltration rate is taken as the difference between rainfall and runoff rates. Baver (5) and Kohnke (37) described several methods in each group.

The cylinder method of Musgrave (48) and the square-foot apparatus of Pearse and Bertleson (59) are two of the smallest and least complicated infiltrometers. Musgrave's infiltrometer consisted of a metal

cylinder 6 inches in diameter, which was jacked into the soil to the B horizon. A 1000 cc dispersing burette was centered over the cylinder and a perforated disk placed on top of the soil to prevent the development of turbidity when water was applied. A head of 4 to 5 mm of water was maintained above the perforated disk during the measurement.

The square-foot apparatus of Pearse and Bertleson (59) was used to spread a thin film of water at a constant rate over an area of one square foot (19 3/16 inches by 7 1/2 inches) and to measure the water which ran off and was not absorbed by the soil. Water was not applied as simulated rainfall but was applied at the uphill side of the plot in such a manner that it was spread out as a thin layer and flowed downhill across the plot. Water absorbed or infiltrated was determined by difference between the amount applied and that which ran off.

Duley and Domingo (17) described a small plot procedure which they used for studying the effects of surface condition and surface protection on the intake of water. Peele and Beale (62) developed a laboratory procedure using simulated rainfall for determining infiltration rates of disturbed soil samples. They found that the infiltration obtained by their laboratory infiltrometer, the so-called type-F field infiltrometer, and infiltration from natural rain storms placed the soils studied in the same order.

Pereira (60) developed a laboratory test to measure the ability of the soil surface to accept continuous heavy rainfall. Soil cores, 4 inches in diameter and 3 inches deep, of undisturbed structure were brought to a standard moisture tension of 20 cm of water, and subjected to heavy artificial rainfall. The drainage tension was maintained at a constant value, and the rate of infiltration was measured. The test was used to measure the effects of grass on rainfall acceptance of an East African sandy loam. The results obtained indicated that "surface capping" was reduced significantly by both 2 and 3 years of grass.

Adams et al. (1) developed a portable rainfall-simulator infiltrometer for making infiltration, runoff, and soil erosion measurements on soil in place. Field data obtained with the apparatus on the Edina silt loam, after 30 minutes of artificial rainfall, showed that the infiltration rate for corn in a corn-oat-meadow-rotation (0.70 inch per hour) was significantly greater than for continuous corn (0.36 inch per hour).

The rainfall simulators previously described for studying runoff and erosion have also been used to measure infiltration rates. Infiltration data obtained by rainfall simulators has been shown to be lower than that with ring infiltrometers. This has been explained by Free et al. (29) as caused by the turbid infiltrating water produced by the impact action of the simulated rain.

Infiltration is the process involved when water enters the soil surface. Percolation is the process in which water moves through the soil. The rate at which water moves through a saturated profile is limited by the permeability and thickness of the least permeable layer. In many soils the least permeable layer is in the B horizon. Nelson and Muckenhirn (51) found that the low minimum infiltration rates, or "field percolation rates," of the Spencer silt loam and the Superior clay loam, and the high rates for Marathon and Miami silt loam could be attributed to the permeability of the B_2 horizons and substrata. The immediate soil

surface may be the limiting layer for many cultivated soils. Duley (16) observed the formation of a thin, compact layer at the surface of a soil and presented a number of photomicrographs clearly showing a surface crust or dense layer. Duley concluded that the sealing of the surface was not due to an increase of fine material but rather to the compact structure formed by the fitting of finer particles between larger ones. Hendrickson (35) observed that very thin layers of silt and clay sediments applied in suspension quickly "blanket" flat sand surfaces or effectively clogged the pores in such a way as to impede the entry of water into the soil. Duley and Kelly (18) concluded that there might be a greater variation between infiltration rates obtained under different surface conditions on a single soil than would be shown by different soils having the same surface conditions.

Ellison and Slater (25) found infiltration rates to be highly sensitive to the quantity of soil carried by raindrop splash. They concluded, for the soils studied, that duration of rainfall, soil carried by raindrop splash, aggregation and clay content of the soil were the principal factors affecting the infiltration rates. Free et al. (29) found a definite association of infiltration with all indices of large pores, or with those factors affecting pore size. They particularly regarded "noncapillary" porosity, degree of aggregation, organic matter, and amount of clay in the subsoil as determinants of infiltration.

Duley and Kelly (18) observed that the infiltration rate decreased slightly with increase in slope. Borst and Woodburn (8) found no relation between infiltration rates and slope. Neal (50) stated that infiltration was not affected by either the slope or the rainfall intensity but varied inversely as the square root of the initial soil moisture content. The initial soil moisture content had a greater effect on the rate of infiltration during the first 20 minutes than any other factor. Tisdall (70) stated that antecedent soil moisture percentage plays an important part in the early stages of an infiltration application. He suggested the use of regression equations, obtained in his study, as a means of correcting infiltration data to a common antecedent soil moisture tension. He concluded that comparative infiltration measurements should be made when the soil is at the same moisture content or at the same moisture tension.

Smith et al. (66) found that increase in organic matter content by barnyard manure significantly increased the infiltration capacity of Clarion loam. Free and Palmer (30). in a laboratory study, observed that water entering closed columns of sand by gravitational and capillary movement compressed the air below the advancing moisture front. Musgrave and Free (49) found that increasing the average percentage of pore space by surface cultivation markedly increased the rate of infiltration on the Marshall silt loam. They concluded that the effect of close vegetation was to reduce the velocity of surface movement and thus allow more time for infiltration to take place.

Osborn (54, 56) found that the effectiveness of cover was directly proportional to quantity, and that the quantity of cover was more important than the kind of cover in protecting soil from raindrop impact. From 5000 to 6000 pounds per acre of cover were required to provide essentially complete soil protection. Measurements by Osborn (57) of soil splash on bare plots of range and crop land showed wide variations in the

susceptibility of soils to movement by raindrop impact. In a standard test, soil movement on crop land plots ranged from 33,198 to 225,565 pounds per acre and on range and pasture it varied from 8832 to 160,339 pounds per acre.

Free (28) described a technique for studying the effects of natural rain under controlled conditions. He found that for surface soils the average loss per inch of rain varied from 5 to 7 tons per acre; "splash" losses were 50 to 90 times "wash-off" losses; wash-off from slopes facing the storm were 3 times those facing away from its direction. Free concluded that wash-off losses appeared to be more closely related to the field behavior of soils and provided a better index of the erosiveness of storms than did splash loss.

Laws and Parsons (39) found that the median drop size appeared to be a fairly strict function of rainfall intensity, and that the upper limit of drop size for intense rains was about 7 mm in diameter. They stated that the erosive power of intense rainfall per unit-volume will be greater, because of the larger drop size, than the erosive power of low intensity rains.

Ellison (21), in experimental studies of raindrop splash, reported maximum distances of splash for drops of different sizes falling at several velocities. Results of this study also showed that the samples of splash contained a greater percentage of aggregates smaller than 0.105 mm than the original soil, indicating a breaking down of the aggregates under raindrop impact. Ellison concluded that there are three distinct actions in the raindrop erosion process as follow: (a) the breaking down of soil aggregates, (b) displacement and transportation of the soils, and (c) making the water turbid with suspended material which reduces infiltration.

Ellison (22) suggested that the storm energy dissipated on the soil be determined by measuring the soil carried in the raindrop splash, based on the fact that an increase in drop impact or number of drops caused an increase in the amount of soil splashed. Ellison also reported that a variation in either drop size or drop velocity caused a change in the infiltration rate of the soil.

Ellison (23) stated that the quantity of soil detached will be proportional to the detaching capacity of the falling raindrops and the detachability of the soil, which he expressed in an equation modified to show the effectiveness of vegetation in absorbing part of the raindrop energy. Ellison also discussed methods of determining the factors of his erosion equation.

Air Permeability and Aeration Pore Space

The rate at which the water will move through a profile—obviously related to soil erodibility—is dependent upon the size and continuity of the channels or pores and increases with pore size. Earlier workers referred to these larger pores as "noncapillary" pores and the smaller pores as "capillary." Baver (3, 5) refers to the noncapillary porosity as being from zero tension to the flex point of the moisture retention curve, as it appeared to be closely associated with the rate of water movement through a column. The fact that the term noncapillary porosity has

never been defined in terms of tension of pore size has led to considerable confusion in its use.

Nelson and Baver (52) found a better correlation between pores drained at a tension of 40 cm of water (pF 1.6) and the percolation rate than at any other tension. They suggested, where only one tension was to be used, that 40 cm of water (pF 1.6) would be the logical tension to get the most information on the water and air permeability of a soil. Smith et al. (67) found a relationship between percolation rates and effective pore-size distribution that was best expressed in the following porosity factor:

$$\text{\% pores drained at 10 cm} + \frac{\text{\% pores drained between 10-40 cm}}{4} + \frac{\text{\% pores drained between 40-100 cm}}{10}$$

They stated that pores drained at 40 to 100 cm tension made very small contributions to percolation and could be omitted except for soils with very slow rates. Bendixen and Slater (6) suggested a "time drainage" procedure of one hour at 60 cm of tension for determining the permeability of soils under tension flow. This type of determination was suggested to support soil survey characterizations of permeability.

More recent trends seem to be toward making complete moisture retention curves rather than use of a single tension. From this information, pore-size distribution can be determined by a method described by Leamer and Lutz (40).

It is generally agreed that the percolation of water through a soil column is definitely a function of the amount and size of the large pores, pore continuity, and directness. Baver (5) states that most of the experimental evidence seems to suggest that the factors of porosity which limit air permeability are similar to those affecting water movement. Buehrer (11), in investigations on the flow of air through lead shot, showed that air permeability varied directly as the square of the average diameter of the particle. In other words, as the size of the pores increased, permeability became greater. Buehrer proposed a quantitative definition of soil structure in terms of the flow of air or air permeability.

Dobryakov (15) described a method for determining soil structure by measuring the rate of intake of air under constant pressure into the soil before and after moistening. He proposed a structural classification based on the air permeability results obtained 60 minutes after moistening the soil with a definite quantity of water.

Aggregation

Lutz (42) stated that the "nonerosive" nature of the Davidson clay was largely due to the high degree of aggregation of the B-horizon into large porous stable granules; the erosiveness of the Iredell was due to its ease of dispersion and the dense, impervious B-horizon. Elson and Lutz (26) investigated the relation between aggregation and erosion and concluded that better aggregation resulted in less soil erosion. Lillard et al. (41) observed that the extent to which the silt and clay was aggregated in the surface soil of a Dunmore silt loam appeared to have more

influence on erodibility than the physical nature of the subsoil. Rai et al. (63) subjected aggregates of various sizes to simulated rain falling 7 feet and found that the intensity of soil erosion progressively increased as aggregate size decreased from 1000 to 500 μ and less.

In most aggregate studies some modification of the Yoder method (74) of aggregate analysis is used. In many methods the soil sample has been allowed to become air dry before testing, as recommended by Yoder. McCalla (43) devised a method of determining the stability of soil structure to water drops falling a distance of 30 cm on a lump of soil. He concluded that the action of the falling water drop on structure was largely through wetting and swelling which loosened the lump so that a drop could disintegrate the structure.

Johnston et al. (36) found that the size distribution of soil aggregates was influenced by the cropping system, with the number of large sized aggregates being in the order bluegrass > clover > oats > rotation corn > continuous corn. The average annual soil loss decreased as the number of larger aggregates increased. Wilson and Browning (72) reported that the percentage aggregates greater than 0.25 mm for different crops were in a similar order. The order was reversed for soil loss and runoff. Wilson et al. (73) found the percentage aggregates greater than 2 mm to be higher in August than in May or November. Gish and Browning (32) found for the Marshall, Belinda, and Clarion soils, that aggregation under four rotations decreased in the order: continuous corn < rotation corn < rotation meadow < bluegrass. For the same soils the number of large stable aggregates increased from spring to a peak in midsummer and then declined gradually throughout the remainder of the growing season. They also observed that the moisture content of the soil at the time of sampling influenced the amount and stability of soil aggregates.

Erosion Indices

Middleton (45) was one of the first to try to obtain an index of soil erodibility based on the physical properties of the soil. He considered that the outstanding characteristics which differentiated soils with respect to erosion were the dispersion ratio, the ratio of colloid to moisture equivalent, and erosion ratio. The dispersion ratio, expressed in percentage, was defined as the ratio of the total weight of silt and clay in the nondispersed sample to the total silt and clay in the dispersed sample. The erosion ratio was equal to (dispersion ratio)/(colloid-moisture equivalent ratio). Middleton considered the dispersion ratio as the most valuable single criterion and suggested that soils with a dispersion ratio less than 15 be classed as nonerosive. The dispersion ratio is a function of the ease of dispersion and of the mechanical composition of the soil.

Cook (13) suggested that an "erodibility index" or a measure of erodibility be developed, based on some type of field test or measurement. He suggested as a field measurement the use of a standard plot of small dimensions to which a fixed quantity of water should be applied by a standardized artificial rainfall or by flowing across the surface at a

fixed rate. Peele (61) thought the percolation rate, suspension percentage, and dispersion ratio were good indices of the relative erodibility of soils, and that the rate at which water percolates through a soil was a more accurate index of the susceptibility of a soil to erosion than its water-holding capacity. Basu and Puranik (2) constructed a rainfall simulator to be used in studying the susceptibility of Indian soils toward erosion and for classifying the soils from the point of view of their erodibility index.

Voznesensky and Artsruui (71) developed an equation or formula for an index of erodibility based on laboratory measurement of dispersion, aggregation, and water-retaining capacity. Gussak (34) devised a flume to measure the erodibility of soils based on the volume of water required to wash away 100 cc of soil by a surface stream of varying velocity. Browning et al. (10) developed a conservation guide for all soils mapped in Iowa, to be used in calculating the limit of the slope length for various combinations of rotations and conservation practices. They divided the soils of Iowa into seven groups and gave the rotation soil factors for eleven different crop rotations for each group. Thompson (69) described a method based on Browning's data obtained at Clarinda, in which the soil loss in tons per acre was calculated for a soil under various rotations and conservation practices.

Gardner and Lauritzen (31) made a laboratory study of the silt content of water at the downstream end of flumes of varying lengths with various combinations of stream size and per cent slope. They used the equation of continuity to develop equations for estimating the rate and depth to which soil will wear down for various slopes and stream sizes. The experimental data obtained in the laboratory with the Greenville silt loam conformed qualitatively with the basic equation which they had developed.

METHODS OF INVESTIGATION

Field Investigation

The field investigation consisted of the measurement of infiltration, runoff, and erosion resulting from the application of artificially applied rain to areas of soil 6 inches in diameter, delimited by thin-walled cylinders, called infiltration cylinders, driven 6 inches into the ground. The runoff was caught in a circular trough surrounding each infiltration cylinder. The trough extended downward below the soil surface into an annular cavity dug into the soil. The runoff from the runoff trough was separated into liquid and solid material. The solid material is called erosion and consists of wash and splash erosion. The field investigation consisted further of the determination of the air permeability of the soil at several soil moisture levels with a gasometer type air permeameter described below.

Standard Conditions

In order to evaluate the soil factor, or that factor in soil erosion attributed to different soil types, it is essential that all of the other factors of erosion be maintained at a constant level. It was decided that the factors of rainfall, slope, cropping history, soil surface condition, and initial moisture level of the soil would be maintained as uniformly as possible under field conditions. Other factors affecting the erodibility of a soil, such as aggregate stability, aeration pore space, and field percolation rate, were considered as part of the properties constituting the soil factor. The following conditions were to be maintained for each soil studied:

1. Rainfall. Intensity of 4 inches per hour $\pm$ 10 per cent and a total rain of 2.00* inches (0.5 hour duration of rain).
2. Slope. Zero per cent slope was to be maintained. The infiltration cylinder was checked for level by use of a spirit level.
3. Cropping history. All sites were to be in fall of the oat phase of a corn, corn, oat, meadow (C-C-O-M) rotation.
4. Initial moisture level. All infiltration a d runoff determinations were to be made with the soil at field capacity. An excess of water was added to each plot to be studied and field capacity was considered as being the moisture level 24 hours after the soil was wet for the coarser textured soils, 48 hours for the intermediate textured soils and 72 hours for the finer textured soils.
5. Soil surface condition. To be loosened to a depth of 0.5 inch prior to soaking the soil to bring it to field capacity.

The rainfall intensity of 4 inches per hour was selected as a rate sufficient to produce erosion and was an intensity which occurred in the area studied. Information obtained from integrated histograms on intensity-time duration rainfalls prepared by Engelbrecht (27) showed that in the last 22 years, 25 5-minute duration rainfalls had occurred with intensities of 3.6 to 4.8 inches per hour and seven with intensities varying from 4.8 to 6.0 inches per hour. During the same period ten 10-minute duration rainfalls, varying from 3.6 to 4.8 inches per hour, and eight 15-minute duration rainfalls, varying from 3.2 to 4.0 inches per hour, had occurred. This information was prepared from Weather Bureau data collected for Des Moines, Iowa. Maximum 30-minute precipitation (65) for the area within which the studies were conducted has approached or exceeded 2 inches as shown for the following points:

Des Moines, Iowa	1.91 in.	Omaha, Nebraska	2.32 in.
Keokuk, Iowa	1.95 in.	Sioux City, Iowa	2.73 in.
La Crosse, Wisconsin	1.99 in.		

The above values were for rainfall data through 1945 with periods of record of 10 years or more for each station.

*The average quantity applied was actually 2.01 inches.

Soils and Sites Studied

Eight soils were selected to be studied ranging in texture from a loamy fine sand to a silty clay loam. A textural variation in soils was desired to provide maximum contrast of the data to be obtained. The soils selected for study and their locations are given in Table 1. The descriptions of these soils are given in Appendix A (page 532).

Table 1. Soils and locations of sites studied.

Soil type	Location	Farm operator
Clarion loam	1 1/2 miles E of Ames, NW 1/4, Sec. 31, T84N, R 23 W	Albert Woods
Webster silty clay loam	Rotation plots, Iowa State College Agronomy Farm, Ames, Iowa	
Thurman loamy fine sand	1 mile E of Ames, NE 1/4, SW 1/4, Sec. 12, T83N, R 24 W	Carl Sampson
Marshall silt loam*	Rotation plots, Clarinda Experiment Station Farm	
Ida silt loam	SE 1/4, SE 1/4, Sec. 7, T83N, R 43 N	F.D. Mings
Monona silt loam*	Near Western Iowa Experiment Farm, NW corner NW 1/4, NW 1/4, Sec. 27, T84N, R 43 W	K.H. Witzel
Grundy silty clay loam	Near Beaconsfield, Iowa, SW 1/4, Sec. 26, T70N, R 28 W	Riley McAlexander
Shelby loam	Near Beaconsfield, Iowa, SW 1/4, Sec. 26, T70N, R 28 W	Riley McAlexander

*Most of A horizon appeared to have been removed by erosion.

The sites to be studied were located, tentatively, by a preliminary survey from the road to find fields which were in the rotation desired, and a more detailed inspection by use of a soil auger was made in the field. Six of the soils studied were on privately owned land and two were in rotation plots supervised by the Iowa Agricultural Experiment Station.

Special Field Equipment

A portable rainfall-simulator infiltrometer, previously described by Adams *et al*. (1), was the device used to apply the artificial rainfall for

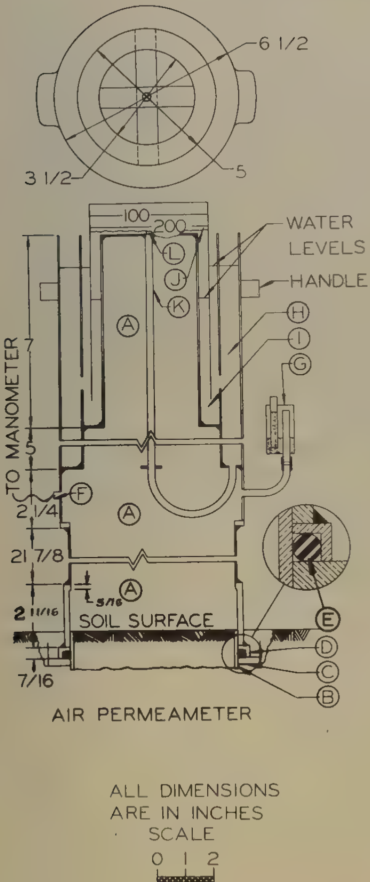
Fig. 1. Air permeameter in field use. In the background can be seen several areas previously moistened and covered with sheet aluminum.

runoff, infiltration, and erosion measurements.*

A modification of the gasometer type air permeameter described by Grover (33) was used to make air permeability measurements. This type of air permeameter provides a supply of air at a constant pressure to the soil sample. The device has the appearance of a long tube (Fig. 1) with a float at the top. In Fig. 1 one sees, surrounding the base of the long tube, a circular ring of galvanized sheet metal driven into the soil. The galvanized ring, 18 inches in diameter, is not a part of the air permeameter but is used in connection with the application of water to the soil to bring the soil in and about the sample area to field capacity.

The air permeameter is shown diagrammatically in Fig. 2. The device was constructed in such a manner that the base of the air chamber (A) would fit over the top of the infiltration cylinder (B) (used also to contain the soil sample on which rainfall is applied for the determination of infiltration, runoff, and erosion) and rest on the runoff trough (C). A shoulder (D) on the lower edge of the air chamber is seated against a 1/4-inch thick, 6-inch inside diameter (I.D.) rubber O-ring (E) to form

*The raindrop application consisted of 1/4 inch O.D. glass capillary tubing (0.047 inch diameter bore, 1 inch length) with 0.040 inch diameter "Chromel-A wire supported in the capillary.



A = air chamber

B = infiltration cylinder

C = runoff trough

D = O-ring shoulder

E = rubber O-ring

F = manometer tube

G = air inlet valve

H = outer annular water tank

I = inner annular water tank

J = small float

K = float guide tube

L = float guide rod

Fig. 2. Assembly drawing of air permeameter showing constructional details; jagged lines across the drawing indicate omission of sections of vertical tubing.

an air seal between the air chamber and the runoff trough. As an additional seal and to aid in detecting air leaks during an air permeability measurement, a runoff spout (not shown) on the infiltration cylinder was plugged with "Absorene" brand noncrumbly type wallpaper cleaner and the runoff trough filled with water. Any air leaks would be revealed by air bubbles rising through the water.

A manometer tube (F) and air inlet valve (G) were located in the upper portion of the air chamber, below an outer annular water tank (H). The

air-inlet valve (G) permits air to enter the air chamber after a run is over and, as Grover has described, also measures the air pressure in the air chamber during a run.

Two interconnected annular water tanks of different size were located at the upper part of the permeameter, partially covering and enclosing the upper portion of the air chamber. The inner annular water tank (I) was designed for use with a small float (J), graduated in 100 ml subdivisions, which was used for slowly permeable soils; the outer annular water tank (H) was for use with a larger float (not shown) having 500 ml subdivisions for more permeable soils. The small float was made from a Superoxol can and the large float from a can in which technical grade sodium hydroxide is shipped. Both floats were counter-balanced so as to have a pressure of approximately 3 cm of water. A float guide tube (K), provided to keep the float (J) or the large float centered, was held in place by a narrow support across both the top and bottom of the water tanks and was connected to the outer annular water tank so as to provide water for lubrication between the guide tube and float guide rod (L). The tops of the water tanks were used as the indices from which to measure the distance per unit time that the floats fell. The air chamber was extended in height, compared with Grover's, so that the tops of the water tanks were about three feet above the ground to facilitate reading the floats.

The permeameter was made entirely from brass plate or tubing, except for the floats as noted, and except for the largest section of tubing seen in Fig. 1. This section of tubing, 21 7/8 inches long (Fig. 2) and comprising part of the air chamber was made from 6-inch I.D. 1/16 inch wall seamless steel tubing. All steel surfaces were coated with Ford Motor Company brand Chrome Saver to prevent rust. All joints and connections were soft soldered.

Field Operating Procedure

After the soil was located in the fall of the oat phase of the rotation, a 21 by 9 foot rectangle was staked out on an area which had essentially zero slope. The rectangular area was then subdivided into 21 squares, with sides of 3 feet, which were designated as plots. The plots were numbered from left to right, starting with number one as the southeast plot when the long axis of the area ran from east to west, and with the southwest plot when the long axis ran north and south. Ten numbers were drawn at random to select the plots in which the measurements were to be made. The vegetation standing on the plots selected was clipped at the soil surface and all extraneous material removed from the surface of the plot. An infiltration cylinder was placed near the center of each plot selected, making certain that the cutting edge of the cylinder did not rest on or next to the root of any of the legumes which had been clipped.

The infiltration cylinder was installed in the manner described by Adams et al. (1), and the soil was wetted to field capacity in the following manner. The large, 18-inch diameter galvanized sheet metal rings (Fig. 1) were driven 4 inches into the ground surrounding the previously placed infiltration cylinders. Two burlap bags were then placed over

each soil surface inside the delimited areas and 5 gallons of water were carefully poured on the bags at a position next to the galvanized sheet metal ring which served as a retaining wall. After all the water had been added the burlap bags were removed and a 2-foot square of aluminum insulation paper was tied over the sheet metal cylinder. The installation was then allowed to stand until the added water had drained to a moisture tension near field capacity.

After the soil had been covered for a sufficient period of time to come to an equilibrium approximating the field capacity, the soil was uncovered and allowed to dry for an hour or two. The drying period was necessary as water condensed within the covered cylinder and dripped back on the soil surface too wet to work with until it had been allowed to dry somewhat. The surface inch of soil was removed from the area between the infiltration cylinder and the galvanized iron ring and the soil sieved through an 8 mm sieve. The soil passing through the 8 mm sieve was air dried and saved for laboratory analyses.

An air permeability measurement was made when the soil moisture was at field capacity and before the infiltration measurement, in the following manner. The runoff trough (C) was thoroughly cleaned and rinsed. The runoff spout was plugged with the "Absorene" brand, non-crumbly wallpaper cleaner, and the rubber O-ring fitted over the infiltration cylinder. The air permeameter was set over the infiltration cylinder in such a manner that the O-ring was forced down against the runoff trough and the O-ring shoulder (D) of the air permeameter. The runoff trough was then filled with water and the trough checked for leaks, while a float was allowed to move downward in the same manner as during an air permeability measurement. If no leaks were noted, a minimum of three air permeability measurements were made and the air temperature taken in the shade. Air permeability was calculated in absolute units (μ^2) by the equation given by Grover (33), assuming 95 per cent relative humidity. The procedure used to obtain the viscosity of air at 95 per cent relative humidity at various temperatures is given in Appendix B (page 540).

After making the air permeability measurements, the air permeameter and O-ring were removed and the runoff trough rinsed and cleaned out. The rainfall simulator was assembled and operated as described by Adams *et al*. (1).

Laboratory Procedures

The pint milk bottles containing the runoff samples collected in the field were taken to the laboratory and runoff, infiltration, and erosion determinations made as described by Adams *et al*. (1).

Moisture Retention and Bulk Density Determinations

The cores collected in the field were stored in a constant temperature room at about 38°F until all field work was finished, to keep bacterial activity or any microbiological changes to a minimum.

The moisture retention data were obtained by using the method

described in the USDA Agricultural Handbook No. 60 (64, p. 110) utilizing porous ceramic disc equipment and a so-called pressure cooker apparatus. Each core sample was covered with a plastic lid and placed on a porous ceramic disc. The plastic lids and ceramic discs were fastened to the brass cylinders by stretching rubber bands across the lids and attaching the bands to hooks at the opposite edges of the ceramic discs. Core samples were saturated from the bottom up by slowly raising the water level to nearly the height of the cylinder. The samples were allowed to stand in the water 48 hours before any tension was applied. Moisture retention was determined at the following water tensions: 0 cm, 10 cm, 30 cm, 60 cm, and 100 cm, 1/3 atmosphere, and 1 atmosphere. The 0 and 10 cm water tension values were determined on a blotter pad tension plate. All higher values were determined in the pressure cooker apparatus. Samples were allowed to stand for 24 hours at the two lower tensions of 0 and 10 cm, and at the higher tensions until equilibrium was attained. The data obtained were used to calculate the percentage moisture by volume at the different tensions and were plotted as moisture-tension curves.

After the moisture retention value was determined for 1 atmosphere of tension, the core samples were oven-dried. The bulk density was then calculated for each core sample using the oven dry weight of the sample and the volume of the core (64, p. 121).

Aggregate[1] Stability in Water

The soil samples collected in the field were air dried and split into two equal portions. One half was used for aggregate water-stability analysis and the other half for determining the dispersion ratio as described below. Aggregate water-stability was determined by a modification[2] of the aggregate-size distribution procedure in USDA Handbook No. 60 (64, p. 124), as follows:

The half of each sample saved for aggregate analysis was passed, without forcing, through a 5 and a 2 mm sieve. The portion remaining on the 5 mm and that passing through the 2 mm sieve were discarded. A 25-gram sample for analysis was taken from the portion retained on the 2 mm sieve. The sample was then added to the top sieve of a nest of sieves, which was oscillated vertically, with a stroke of 1 inch, under water for 30 minutes. The mechanism was adjusted so that the screen made contact with the water surface when the oscillation mechanism was at the top of the stroke. The sieve set consisted of a series of sieves with openings of 2, 1, 0.5, 0.25, and 0.10 mm. That portion of the sample retained on each sieve at the end of 30 minutes was washed into evaporating dishes and oven-dried at 105°C for 24 hours. The oven-dried material was weighed to 0.01 gram and the percentage of the total weight of each fraction was computed on an oven dry basis. The per cent remaining on each screen was reported.

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[1]The term aggregate as used herein is understood to include some primary particles as well as true aggregates.

[2]Mimeographed procedure prepared by the North Central States Soil Research Technical Committee NC-17, January 1955.

Dispersion Ratio

The dispersion ratio was determined for the 0.02 mm size fraction by a modified pipette analysis for both a chemically dispersed and non-dispersed sample. The portion of the sample saved for pipette analysis was corasely ground to pass a 2 mm sieve. The procedure for the chemically nondispersed sample was as follows: A sample of air-dry soil, equivalent to 10 grams of oven-dry soil, was weighed and placed in a quart milk bottle with sufficient distilled water to make a total volume of 900 cc. The bottle was tightly stoppered and shaken end-over-end by hand for 60 seconds. A stop watch was started at the end of shaking and a pipette withdrawal made at 10 cm depth at the required time interval for the 0.02 mm size fraction to have settled below 10 cm. The pipetted sample was then quantitatively transferred to a 50 cc weighed beaker and oven dried for 24 hours at 105°C. The oven-dried sample was cooled in a dessicator, weighed on an analytical balance to 0.0001 gram, and the percentage of the total oven-dry weight of the 0.02 fraction calculated.

A similar procedure was followed for the chemically dispersed analysis except that the 10 gram oven-dry sample was added to a high speed mixer cup. Then 250 cc of distilled water and 10 cc of sodium hexametaphosphate solution* were added and the sample mixed by the mixer for 10 minutes. The sample was then quantitatively transferred to the milk bottle and the volume diluted with distilled water to 900 cc. The same procedure for both the dispersed and nondispersed was followed from this step on.

The dispersion ratio (45) was calculated by dividing the total oven-dry weight of 0.02 mm and finer fraction from the chemically nondispersed analysis by the total oven-dry weight of the same size fraction of the chemically dispersed sample and multiplying the quotient by 100.

$$\text{Dispersion} = \frac{\text{gms oven-dry material} \leq 0.02 \text{ mm chemically nondispersed}}{\text{gms oven-dry material} \leq 0.02 \text{ mm chemically dispersed}} \times 100$$

RESULTS

Runoff

Results of the runoff rates and total runoff for the eight soils tested are given in Table 2. The values are for 2.00 inches of rain applied in approximately 1/2 hour at the constant nominal rate of 4 inches per hour. The values are average values for a number of replicates, in no case less than eight, as given in the table caption. The standard error for each runoff value is given in the body of the table.

*35.7 grams sodium metaphosphate and 7.94 grams sodium carbonate in one liter of solution.

Table 2. Runoff rates and total runoff on eight Iowa soils from 2.00 inches of rain applied in approximately 1/2 hour with the rainfall simulator. Determinations were made in the fall of the oat phase of a corn-corn-oats-meadow rotation with the soil initially at the field capacity and with the surface cultivated. R is the time after zero when runoff begins; F is the time rainfall ceases. Values of runoff are averages for 10 replicates for Grundy, Monona, Marshall, Webster, and Thurman; of 9 replicates for Clarion and Ida; and of 8 replicates for Shelby. Numbers in parentheses are standard errors. Soils are listed in order of 20 to 25 minute runoff rate. Dashed horizontal lines show groups of soils, the average values of which differ from each other statistically significantly.

	R	F	Runoff rate (in./hr.) F or time intervals							Total	Rainfall
			0-R	R-5	5-10	10-15	15-20	20-25	25-F	runoff	intensity
	min.	min.	min.	min.	min.	min.	min.	min.	min.	inches	in./hr.
Grundy	1.43	29.2	0	2.39	3.89	4.03	4.01	4.05	4.12	1.76	4.13
					(0.11)	(0.11)	(0.11)	(0.09)	(0.11)	(0.02)	(0.09)
Monona	1.34	29.4	0	2.67	3.82	3.90	3.99	3.99	3.96	1.76	4.11
					(0.14)	(0.12)	(0.10)	(0.09)	(0.13)	(0.10)	(0.08)
Marshall	1.46	30.1	0	2.35	3.64	3.82	3.83	3.90	4.21	1.75	4.02
					(0.10)	(0.07)	(0.08)	(0.08)	(0.13)	(0.03)	(0.07)
Shelby	1.80	31.4	0	1.45	3.21	3.59	3.70	3.65	3.77	1.64	3.87
					(0.12)	(0.14)	(0.13)	(0.09)	(0.24)	(0.29)	(0.10)
- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
Ida	2.07	30.2	0	1.67	2.84	3.41	3.54	3.58	3.61	1.50	4.00
					(0.14)	(0.08)	(0.08)	(0.10)	(0.08)	(0.03)	(0.05)
Webster	1.91	30.7	0	1.43	2.48	3.09	3.25	3.40	3.46	1.42	3.93
					(0.19)	(0.22)	(0.19)	(0.12)	(0.13)	(0.05)	(0.08)
Clarion	2.16	29.8	0	1.51	2.63	2.90	3.21	3.32	3.42	1.36	4.01
					(0.15)	(0.16)	(0.20)	(0.13)	(0.12)	(0.07)	(0.05)
- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
Thurman	1.98	29.1	0	0.10	0.03	0.12	0.34	0.62	1.08	0.18	4.15
					(0.01)	(0.09)	(0.22)	(0.26)	(0.29)	(0.07)	(0.07)

The soils in Table 2 are listed in the order of decreasing runoff rate for the 20 to 25 minute interval. Also the soils have been grouped, on the basis of the 20 to 25 minute runoff rates, into erodibility classes. The groups are indicated by horizontal dashed lines. Although there is not a definite break in the 20 to 25 minute values for the first seven soils listed, there is a relatively large break between the Shelby and Ida and, therefore, the four soils above and including the Shelby are indicated in the table as one group and the three below the Shelby as another group. The eighth soil, the Thurman (sand)–since its total runoff is decidedly less than any of the others–is indicated as a third "group." The means of the group are statistically significantly different (5 per cent level). The average runoff rate for the three groups of soil is shown plotted against time of rainfall in Fig. 3.

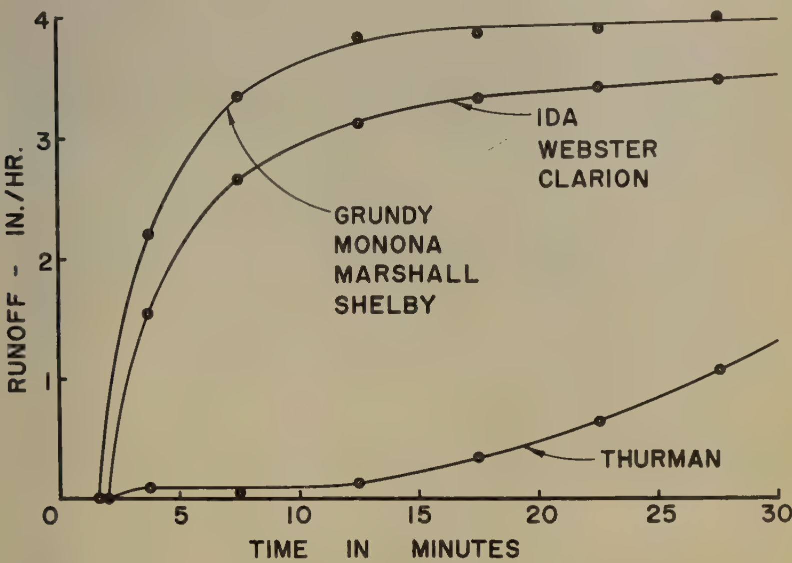

Fig. 3. Runoff rates for three groups of Iowa soils plotted against length of time of rainfall for a nominal 4-inch per hour rain.

In studying Table 2 and Fig. 3 one should observe that all the time intervals are not of equal duration. For example, the first time interval for the Webster is 0 to 1.91 minutes and the last time interval 25 to 30.7 minutes, the numbers 1.91 and 30.7 being listed under the columns R and F. Thus, the total runoff for the Webster, which is 1.42 inches, is related to these values and to other values shown in the table by the relation

$$\frac{(1.43)(5-1.91)+(2.48+3.09+3.25+3.40)(5)+(3.46)(30.7-25)}{60} = 1.42 \text{ inches.}$$

Similar relations exist for other tabulated values. An example for the calculation of a value plotted in Fig. 3 may also be given for definiteness. The runoff rate for the 5 to 10 minute time interval for Grundy, Monona, Marshall, and Shelby (Table 2) is $(3.89 + 3.82 + 3.64 + 3.21)/4 = 3.64$ in./hr. Notice in Table 2 and/or Fig. 3 that, except for the Thurman, the runoff rate rises rapidly in the first 10 minutes for all soils and reaches a fairly constant value after about 20 minutes. In the Thurman (sand) the runoff rate does not become appreciable until after about 15 minutes when it begins to increase rapidly, the increase continuing at the end of the experimentation. In Table 2 the values in the 25 to F column are, in some cases, not consistent with those in the 20 to 25 column. The lack of consistency presumably stems from inability of an operator to shut off, and accurately time, the terminal rainfall.

Infiltration

Infiltration results are tabulated in Table 3. The values are obtained by subtracting runoff rates tabulated in Table 2 from the constant infiltration rates in the last column of Table 2. Thus, for the Webster one may compute from Table 2, for the 10-15 minute interval, the infiltration rate to be $(3.93-3.09) = 0.84$ in./hr., which is tabulated in Table 3.

Table 3. Infiltration rates and total infiltration for the soils and conditions of Table 2; soils are in order of the 20 to 25 minute rate; order is the same as for Table 2.

	Infiltration rate (in./hr.) for time intervals							Total
	0-R	R-5	5-10	10-15	15-20	20-25	25-F	infil- tration
Soil	min.	min.	min.	min.	min.	min.	min.	inches
Grundy	4.13	1.74	0.25	0.11	0.14	0.11	0.09	0.26
Monona	4.11	1.44	0.29	0.21	0.12	0.13	0.16	0.25
Marshall	4.02	1.68	0.38	0.20	0.19	0.14	0.06	0.28
Shelby	3.87	2.42	0.66	0.28	0.17	0.22	0.22	0.38
Ida	4.00	2.33	1.17	0.60	0.47	0.43	0.40	0.51
Webster	3.93	2.50	1.44	0.84	0.68	0.52	0.46	0.59
Clarion	4.01	2.51	1.37	1.10	0.80	0.69	0.61	0.62
Thurman	4.15	4.05	4.12	4.04	3.82	3.54	3.07	1.84

Other values in Table 3 are obtained similarly. In particular, column one of Table 3 has the same values as the last column in Table 2, since by definition of the time R there is no runoff during the period 0 to R. Standard deviations are not given in Table 3 since these will be the same as in Table 2. Values in Table 3 may depart one or two digits in the second decimal due to rounding of figures. Originally, computations were made to three decimals.

For infiltration, the soils in Table 3 take the same grouping as for runoff, the listing now, however, being in order of increasing value of infiltration rate in the 20 to 25 minute interval. The average infiltration rate for the groups are shown plotted against time in Fig. 4. Notice in Fig. 4 that the infiltration rates for the groups tend to reach a constant value after about 25 minutes, though this is not always seen for the individual soils in Table 3. The lack of consistency which is seen to occur for the intervals 20-25-minute and 25-F is probably, as before, due to inability of the operator of the rainfall simulator to terminate operations accurately.

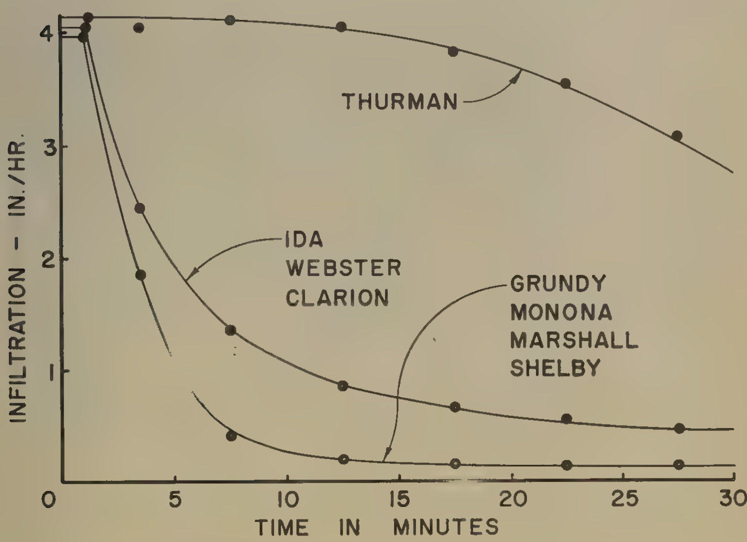

Fig. 4. Infiltration rates for three groups of Iowa soils plotted against length of time of rainfall for a nominal 4-inch per hour rain.

Erosion

The results for erosion are given in terms of wash erosion, splash erosion, and total erosion, these terms being defined as follows. Wash erosion is soil which was eroded or removed in suspension by the runoff water during each 5-minute interval; splash erosion is soil which is retained on the splash shield and in the runoff trough after runoff had ceased; and total erosion is the sum of wash and splash erosion. By the nature of the experimentation, rates of splash erosion could not be determined for the individual 5-minute intervals. But wash erosion rates could be determined add these rates, together with values of the total

Table 4. Wash erosion rates and total wash erosion for the soils and conditions of Table 2; soils are listed, as before, according to rates in the 20 to 25 minute time interval; soil groups are not the same as for Tables 2 and 3.

Soil	R	F	Wash erosion rate (tons/acre/hr.) for time intervals							Total wash erosion tons/acre
			0-R	R-5	5-10	10-15	15-20	20-25	25-F	
Marshall	1.46	30.1	0	2.47	3.42	2.84	2.38	2.03	2.09	1.20
					(0.16)	(0.21)	(0.17)	(0.13)	(0.19)	(0.06)
Webster	1.91	30.7	0	1.08	1.96	2.00	1.71	1.70	1.70	0.83
					(0.27)	(0.24)	(0.26)	(0.24)	(0.36)	(0.11)
Grundy	1.43	29.2	0	2.06	2.54	2.08	1.77	1.58	1.38	0.88
					(0.22)	(0.20)	(0.20)	(0.18)	(0.16)	(0.09)
Monona	1.34	29.4	0	2.58	2.53	1.91	1.68	1.56	1.49	0.90
					(0.20)	(0.17)	(0.15)	(0.18)	(0.19)	(0.08)
Clarion	2.16	29.8	0	1.09	1.86	1.56	1.64	1.32	1.00	0.67
					(0.15)	(0.11)	(0.14)	(0.12)	(0.11)	(0.04)
Ida	2.07	30.2	0	1.39	1.46	1.31	1.11	0.99	0.91	0.55
					(0.22)	(0.18)	(0.14)	(0.13)	(0.13)	(0.07)
Shelby	1.80	31.4	0	0.99	1.42	1.10	1.04	0.96	0.84	0.52
					(0.14)	(0.10)	(0.14)	(0.13)	(0.10)	(0.05)
Thurman	1.98	29.1	0	0.03	0.02	0.02	0.03	0.07	0.22	0.03
					(0.00)	(0.01)	(0.01)	(0.02)	(0.06)	(0.01)

wash erosion are shown in Table 4. One sees in the table that the wash erosion rates increase rapidly in the first five to 10 minutes and then decrease, at first rather rapidly, and then slowly as the end of a run approaches.

In Table 4 horizontal broken lines are shown which divide the soils into groups according to their wash erosion rates in the 20 to 25-minute time interval and the average rates of wash erosion for these soil groups are shown in Fig. 5.

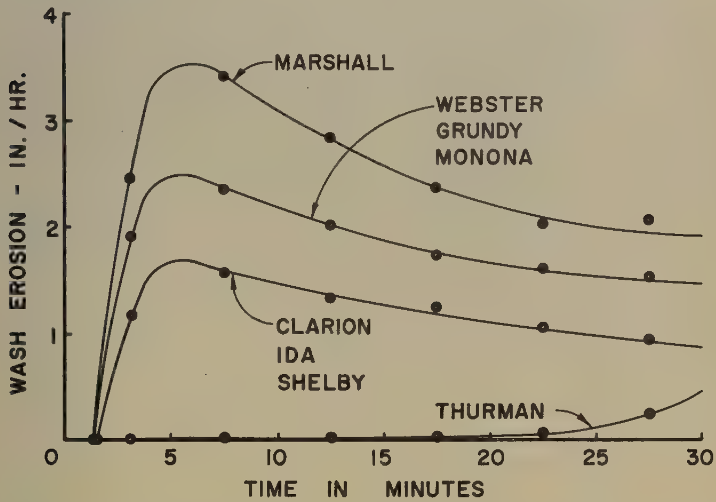

Fig. 5. Wash erosion rates for four groups of Iowa soils for a nominal 4-inch per hour rain applied for one half hour.

Of the soils studied, the Thurman had the lowest wash erosion rate throughout the entire period of rainfall. Even at the end of the rainfall the wash erosion rate (Table 4) was still only 0.22 ton per acre per hour.

Splash erosion and total erosion are shown in Table 5. Here the erosion values are totals for all the (nominal) 5-minute intervals. The table also includes wash erosion and shows, by means of horizontal dashed lines, the grouping of the soils into erodibility classes; the soils in each group are arranged in the order of decreasing erodibility.

The erosion groups in Table 5 are set up on the basis that there be a statistical difference in the means at the 5 per cent level of significance. The soils were divided into four statistically different groups for wash erosion and three different groups for splash erosion and total erosion as shown by the horizontal lines in Table 5. The Thurman was placed in a separate group in both splash erosion and total erosion (see dashed line Table 5) even though there was not a statistical difference between

Table 5. Comparison of wash erosion, splash erosion, and total erosion for eight Iowa soils and their division into groups* which differ statistically. Based on data obtained from 2.00 inches of artificial rain applied with the rainfall simulator.

Wash erosion		Splash erosion		Total erosion	
Soil	Total[a]	Soil	Total[a]	Soil	Total[a]
Marshall	1.20 (0.06)[b]	Thurman	9.47 (1.99)	Thurman	9.50 (1.99)
Monona	0.90 (0.08)	Webster	6.50 (0.84)	Webster	7.32 (0.80)
Grundy	0.88 (0.09)	Grundy	6.18 (0.36)	Grundy	7.06 (0.39)
Webster	0.83 (0.11)	Shelby	5.97 (0.41)	Marshall	6.99 (0.19)
Clarion[d]	0.67 (0.04)	Marshall	5.79 (0.49)	Monona	6.58 (0.32)
Ida	0.55 (0.07)	Monona	5.68 (0.36)	Shelby	6.48 (0.44)
Shelby	0.52 (0.05)	Clarion	4.47 (0.53)	Clarion	5.14 (0.55)
Thurman	0.03 (0.01)	Ida	3.80 (0.26)	Ida	4.34 (0.32)

*Solid lines (read vertically) separate groups in which the means are statistically significant.

[a] Total expressed in tons per acre.

[b] Standard error in parentheses (Sx).

[c] Broken line separates groups of soils based on other physical factors or measurements.

[d] A marginal soil. Fits statistically in either group.

the results obtained for the Thurman and the remainder of the more erodible soils. This separate grouping was established, based on textural differences and also because the total erosion for the Thurman consisted of 99.7 per cent splash erosion. No significant differences were obtained between the means of the Thurman when compared with soils with greater total erosion than the Clarion. There was a statistical difference between the Thurman and Clarion soils. The Marshall soil with 1.20 tons per acre had the most wash erosion for 2 inches of rain and the Thurman with 0.03 ton per acre had the least. The Thurman had significantly more splash erosion than any of the other seven soils.

Table 6. Comparison of wash erosion per inch of runoff for eight Iowa soils.

Soil	Wash erosion per in. runoff (tons/acre)	Soil	Wash erosion per in. runoff (tons/acre)
Marshall	0.686	Clarion	0.496
Webster	0.585	Ida	0.367
Monona	0.511	Shelby	0.313
Grundy	0.503	Thurman	0.150

When total wash erosion was calculated on the basis of tons per inch of runoff (Table 6) the soils remained in the same general order of erodibility, except for the Webster, but the absolute differences were reduced considerably. Such a rating or arrangement makes it possible to compare the erodibility of soils based on equal quantities of runoff. However, since the ability of a soil to absorb and transmit water through its profile is an important factor affecting wash erosion, infiltration should be considered when evaluating the natural susceptibility of different soils to erosion.

Air Permeability

Air permeability data are given in Table 7. Air permeability measurements at 1 and 2-hour intervals were not made on the Shelby and Grundy soils, as it appeared that the soil would freeze before the studies could be completed. Air permeability values were taken for the other six soils at 1 and 2-hour time intervals after rainfall was terminated, as well as at field capacity before rainfall. The values, in general, reflected the textural differences of the soils. The coarser textured soils were more permeable to air at both time intervals. Based on texture, the Thurman sand would be expected to be the most permeable, but 2 hours after rainfall had been terminated the Ida silt loam had recovered 67 per cent of its air permeability at field capacity as compared to 38 per cent for the Thurman at the same time.

Table 7. Air permeability in μ^2 for eight Iowa soils before rainfall, and at several time intervals after 2.00 inches of artificial rain had been applied.

	Air permeability in μ^2			
Soil	Before rain	60 min. after rain	120 min. after rain	240 min. after rain
Webster	1.35 (0.37)**	0.36 (0.15)	0.52 (0.19)	----
Shelby	2.46 (0.35)	----	----	----
Clarion	2.96 (0.49)	0.48 (0.21)	0.71 (0.32)	----
Grundy	2.14 (0.43)	----	----	----
Monona	1.42 (0.19)	0	0.15 (0.13)	0.69 (0.31)
Ida	2.66 (0.33)	1.43 (0.28)	1.79 (0.30)	----
Thurman	2.95 (0.20)	0.95 (0.15)	1.13 (0.14)	----
Marshall	1.97 (0.61)	0.24 (0.11)	0.45 (0.17)	1.09 (0.43)

*Soil near field capacity

**Values in parentheses are standard errors.

Several measurements were made at the end of 4 hours on the Marshall and Monona soils. The air permeability for Marshall had nearly doubled and for Monona it had more than doubled at 4 hours over the values obtained at the end of 2 hours. However, assuming the air permeability was zero at the instant rainfall ceased, the air permeability increased less from 60 to 120 minutes than during the 0 to 60-minute time interval for all soils except the Monona, which did not become permeable until 60 minutes after rainfall had been terminated. A few air permeability measurements were made on some soils after longer periods of time. The results indicated that at the end of 24 hours the Ida soil had almost the same air permeability as at field capacity, and the Clarion soil had recovered about 75 per cent of its air permeability at field capacity.

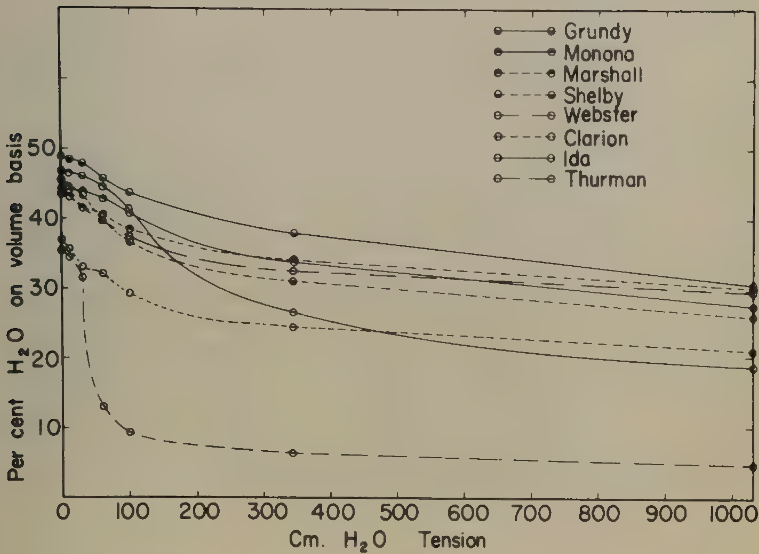

Fig. 6. Moisture retention curves from 0 cm to 1 atmosphere of tension for the eight Iowa soils upon which infiltration measurements were made with the rainfall simulator.

Moisture-Tension Data and Aeration Pore Space

Results of the moisture retention data are shown in Fig. 6. It can be seen that six of the soils varied from 43 to 49 per cent moisture at 0 cm of tension, and from 37 to 44 per cent moisture at 100 cm of tension. The Thurman and Clarion soils were close in moisture retention at 0 cm, but differed widely at 100 cm of tension, having 9.5 per cent and 29.5 per cent moisture, respectively. Only the pore space drained by the lower tensions would be expected to be related to infiltration and erosion in this study, as all soils were presoaked to be near field capacity at the time of rain. On the basis of the pore space drained by the lower moisture tensions (Table 8) the soils could be arranged in two or three groups of infiltration capacity. The Thurman would be expected to have the largest water intake capacity as indicated by the high per cent of pores drained over the 0 to 100 cm range of tension. Based on similar reasoning, the Webster and Shelby soils would have an intermediate water intake capacity, and the remaining soils would be in a group of lower water intake capacity and, conversely, higher runoff and wash erosion. It is recognized that the stability of the surface soil aggregates could have a considerable effect on the infiltration rate even though a large water intake capacity exists.

Table 8. Percentage of pores drained over two ranges of water tension for the eight Iowa soils upon which infiltration measurements were made with the rainfall simulator; soils ordered for 0 to 60 cm tension.

Soils	0 to 60 cm tension		0 to 100 cm tension	
	Percentage of pores drained[a]	Standard error $S\bar{x}$	Percentage of pores drained	Standard error $S\bar{x}$
Monona	1.67	(0.58)	3.73	(0.73)
Marshall	2.90	(0.68)	4.89	(0.73)
Grundy	3.09	(0.65)	5.10	(0.71)
Ida	3.32	(0.84)	6.46	(0.96)
Clarion	3.52	(0.49)	6.19	(0.56)
Shelby	5.86	(0.98)	8.77	(1.04)
Webster	6.48	(0.94)	8.90	(0.99)
Thurman	22.41	(0.62)	25.89	(0.55)

[a]Per cent of total soil volume drained by a given tension.

Table 9. Percentage size distribution of aggregates after wet sieving of dry soil that passed a 5 mm sieve but was retained on a 2 mm sieve; soils ordered according to percentage < 0.10 mm.

Soils	Percentage of sample within each size range					
	5-2*	2-1	1.0-0.5	0.5-0.25	0.25-0.10	< 0.10
Webster	3.8	7.6	15.1	27.8	26.4	19.3
	(0.4)+	(0.5)	(0.7)	(0.6)	(0.8)	(0.9)
Shelby	12.0	10.8	12.2	22.0	22.8	20.2
	(0.9)	(0.5)	(0.4)	(0.8)	(0.6)	(0.7)
Clarion	10.6	9.4	10.2	21.9	26.7	21.2
	(1.1)	(0.6)	(0.5)	(0.5)	(0.9)	(0.9)
Grundy	13.4	10.9	12.1	18.8	18.1	26.8
	(1.5)	(0.6)	(0.4)	(1.0)	(0.8)	(1.6)
Marshall	6.4	5.6	7.0	18.4	22.2	40.5
	(0.5)	(0.3)	(0.4)	(1.9)	(0.5)	(2.0)
Monona	5.9	7.3	7.3	12.6	22.1	44.8
	(0.9)	(0.6)	(0.3)	(0.6)	(1.2)	(1.7)
Ida	17.0	8.7	3.7	5.3	8.8	56.5
	(1.3)	(0.7)	(0.2)	(0.3)	(0.4)	(1.6)

*Dimensions in millimeters.
+Standard error ($S\bar{x}$) in parentheses

Aggregate Stability

Aggregate stability for the 2 to 5 mm size fraction was determined for all soils except the Thurman. Results of the aggregate stability analyses are given in Table 9. Soils which break down into many very small aggregates or primary particles would be considered more erodible then soils which break down into intermediate sized aggregates or remain stable. Based on the percentage < 0.10 mm, the Ida soil aggregates* were the least stable and the Webster the most stable. Using the percentage<0.1mm as an index of erodibility, the soils can be arranged in order of erodibility as follows: Webster < Shelby < Clarion < Grundy < Marshall < Monona < Ida; but this order does not agree with either wash, splash, or total erosion as found in Table 5. Perhaps it is a misconception that erosion as caused by the beating action of rain may be compared with the water stability of soils as measured by the gentle wet sieving process. Surface sealing was observed after rainfall had terminated for the Marshall and Monona soils which both had a high percentage of aggregates < 0.10 mm. The high percentage of 2 to 5 mm water stable particles for the Ida may be partially accounted for by the large amount of root fragments observed and the high free calcium content.

Dispersion Ratio, Size Fraction $\leqq 0.02$ mm and Bulk Density

Dispersion ratio data are given in Table 10. Middle (45) suggested that soils with a dispersion ratio less than 15 could be classed as non-erodible. On this basis, the Grundy, Monona, Ida, Thurman, and Marshall soils would be expected to be erodible. If the magnitude of the dispersion ratio were a definite indication of the degree of susceptibility to erosion, the Ida soils with a dispersion ratio of 30.02 would be expected to be most erodible and the other four erodible soils would possess about the same degree of susceptibility to erosion. Actually, from the data obtained in this study (Table 5), the Ida was one of the least erodible soils, but the Monona, Marshall, and Grundy were in an intermediate to more erodible group. The Thurman had a very low wash erodibility but was highly susceptible to splash erosion.

Dispersion analyses showed that the soils varied in silt and clay content from 5.9 per cent for the Thurman to 65.6 per cent for the Grundy, with the remaining soils varying from 30 to 60 per cent. These values indicate that all the soils were sandier than their soil type name would imply. However, since these samples were all from the surface inch, it is possible that rains since the last cultivation had sorted the surface layer causing it to be coarser than the remainder of the plow layer.

Bulk density values (Table 10) obtained from the cores collected for soil moisture tension measurements varied from 1.25 for the Webster to 1:59 for the Thurman. Except for the Clarion soil, the soils with dispersion ratios less than 15 had lower bulk densities than the soils with dispersion ratios.

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*See footnote, page 504.

Table 10. Dispersion ratio, percentage size fraction $\leq$ 0.02 mm of the surface inch and bulk density for the eight Iowa soils used in the infiltration-erosion study; soils arranged in order of dispersion ratio.

Soils	Dispersion ratio		Percentage size fraction $\leq$ 0.02 mm		Bulk density (g/cc)	
Ida	30.02	(0.99)	35.1	(0.2)	1.32	(0.02)
Thurman	18.78	(1.25)	6.0	(0.1)	1.59	(0.01)
Monona	18.42	(0.57)	49.8	(0.2)	1.37	(0.02)
Marshall	16.58	(0.41)	57.4	(0.3)	1.40	(0.01)
Grundy	15.32	(0.27)	65.5	(0.1)	1.26	(0.02)
Clarion	14.13	(0.67)	32.0	(0.2)	1.55	(0.02)
Shelby	10.27	(0.16)	44.3	(0.3)	1.29	(0.02)
Webster*	7.37	(0.36)**	53.0	(0.2)	1.25	(0.03)

*Each soil was replicated 10 to 12 times for dispersion ratio and percentage size fraction $\leq$ 0.02 mm and from 8 to 11 times for bulk density.
**Standard errors ($S\bar{x}$) are in parentheses.

Correlations

A number of correlation coefficients were calculated and the results are given in Table 11. In the table the expression runoff rate at 22.5 minutes is the runoff rate for the 20 to 25-minute interval of Table 2; and the expression infiltration rate at 22.5 minutes is the infiltration rate for the same interval in Table 3. These 22.5-minute rates, as seen in Figures 3 and 4, are almost steady state values—being near maximum values for runoff, and near minimum values for infiltration.

Correlations of the runoff rate at 22.5 minutes vs. the rate of rainfall* for the Marshall soil, were highly significant at the 1 per cent level. The correlation of the runoff rate at 22.5 minutes with the rate of rainfall for all soils was statistically significant at the 5 per cent level.

The correlations of initial infiltration rate vs. per cent pore space drained by 60 cm, 100 cm, and 1/3 atm of water tension were all highly significant at the 1 per cent level. In other words, there was a close relation between the initial infiltration rate and the percentage of the larger pores which would be open at the field capacity. Correlations of the infiltration rate at 22.5 minutes vs. air permeability at field capacity and vs. air permeability at 60 minutes after rainfall ceased (but not 120 minutes after) were statistically significant at the 5 per cent level. Correlations were highly significant for the minimum infiltration rate vs.

*Rate of rainfall, although kept at a nominal 4 in./hr. for most tests, was varied in certain tests not reported in Tables 2 and 3.

Table 11. The relation of field measurements to various laboratory determinations and to other field measurements as indicated by correlation coefficients and regression equations

Physical measurements correlated[a]	Degrees of freedom	Correl. coeff.	Regression equation y = a + bX
Runoff rate at 22.5 min. vs.			
Rate of rainfall for Marshall	10	0.978**	-0.29+1.04 X
Rate of rainfall (all soils)	80	0.229*	0.41+0.724 X
Initial infiltration rate vs.			
% pore space drained by 60 cm water tension	69	0.705**	2.44+0.07 X
% pore space drained by 100 cm water tension	69	0.721**	2.29+0.07 X
% pore space drained by 1/3 atm. water tension	69	0.711**	1.84+0.07 X
Infiltration rate at 22.5 min. vs.			
Air permeability at field capacity	73	0.259*	0.24+0.22 X
Air permeability at 60 min.	48	0.308*	0.55+0.51 X
Air permeability at 120 min.	43	0.252	0.47+0.33 X
% pore space drained by 60 cm water tension (mean value of each soil)	6	0.978**	-0.30+0.17 X
% pore space drained by 60 cm water tension	69	0.882**	-0.22+0.15 X
% pore space drained by 100 cm water tension	69	0.877**	-0.52+0.14 X
% pore space drained by 1/3 atm. water tension	69	0.788**	-1.31+0.14 X
% water at 0 cm tension (total pore space)	69	-0.651**	7.43-0.15 X
Rainfall rate (Marshall only)	10	-0.297	0.33-0.05 X
% water stable aggregates > 2 mm	64	0.081	0.26+0.005 X
Dispersion ratio	74	0.091	0.48+0.016 X
Wash erosion vs.			
% water-stable aggregates > 2 mm	71	-0.341**	1.01-0.02 X
Rainfall intensity	71	0.307**	-0.18+0.25 X
Splash erosion	81	-0.206	0.87-0.027 X
Dispersion ratio	81	-0.168	0.87-0.01 X
Wash erosion rate at 22.5 min. vs.			
Rate of rainfall (Marshall only)	10	0.266	1.25+0.18 X
Splash erosion vs.			
% water stable aggregates > 2 mm	71	-0.264*	6.30-0.088 X
Rainfall intensity	71	0.279*	0.33+1.27 X
Dispersion ratio	81	-0.081	6.51-0.036 X
Bulk density vs.			
% water retained at 0 cm tension (total pore space)	61	-0.96**	2.54-0.027 X
Runoff	65	-0.64**	1.60-0.16 X
Wash erosion	65	-0.45**	1.49-0.16 X
Splash erosion	65	0.21	1.32+0.01 X
Air permeability at field capacity	64	0.21	1.33+0.02 X
Air permeability			
At field cap. vs. % pore space drained by 60 cm water tension	73	0.191	2.08+0.04 X
at 60 min. vs. " " " " "	49	0.120	0.55+0.01 X
At 120 min. vs. " " " " "	44	0.050	0.79+0.006 X

[a]Correlations are for all soils considered together unless noted otherwise.
*Denotes statistical significance at 5 per cent level.
**Denotes statistical significance at 1 per cent level.

per cent pore space drained by 60 cm water tension (for all soils and the mean value for each soil), 100 cm water tension, 1/3 atmosphere water tension; and per cent water retained at 0 cm tension (total pore space); the correlation with total pore space was negative. Rainfall rate, percentage water stable aggregates > 2 mm, and the dispersion ratio showed no significant relation with the minimum infiltration rate.

There was a highly significant negative correlation of wash erosion vs. per cent water stable aggregates > 2 mm, and a positive correlation of wash erosion vs. rainfall intensity. There was no significant relation for the correlation of wash erosion vs. splash erosion, or vs. the dispersion ratio; however, the correlation of wash erosion vs. splash erosion, although negative, was very nearly significant. There was not a significant correlation of wash erosion rate at 22.5 minutes with rainfall for the Marshall soil, which had the greatest extremes in rainfall rates. Splash erosion showed a significant negative correlation with per cent water stable aggregates > 2 mm, and a positive correlation with rainfall intensity, but no correlation with the dispersion ratio.

As for bulk density, highly significant negative correlations were found between this property and the per cent water retained at 0 cm water tension, runoff, and wash erosion for all soils studied. The correlation between bulk density and splash erosion was positive and almost significant for all soils. Bulk density and air permeability at field capacity were not significantly correlated.

To conclude the results of the correlations, there are included in Table 11 regression equations of air permeability, at several soil conditions, with the per cent pore space drained at 60 cm tension. The correlations were not significant.

DISCUSSION

Soil properties in relation to water erosion may be divided into two types: (a) those properties that affect the infiltration rate, that is, the rate at which rainfall enters the soil, and (b) those properties which resist dispersion and erosion during rainfall and runoff. A summary of such properties, whether measured in the field or in the laboratory, is given in Table 12 and the discussion which follows is keyed thereto.

The volume of large pore space present in a soil is one of the important soil properties affecting the infiltration rate. The air permeability measurements made at field capacity (last column Table 12) and the per cent pores drained by a 60 cm water column tension (next to last column) are measures of the amount of larger pore space available. From these data it can be seen that the Thurman soil, with the highest infiltration rate and lowest runoff, had the largest percentage of pores drained at 60 cm of water tension, and was one of the soils with a high air permeability at field capacity. In general, those soils with 3.09 per cent or less of pore space drained at 60 cm had the lowest 22.5-minute infiltration rates and the highest runoff. Air permeability at field capacity of 2.14 μ^2 or less was also associated with low infiltration rate and high runoff. The exception to this was the Webster soil which had an air permeability at field capacity of 1.35 μ^2, but had one of the highest

Table 12. Summary of field and laboratory physical measurements. Field measurements made with a standard rain of 2.00 inches with an intensity of 4.0 inches per hour $\pm$ 10 per cent delivered by the rainfall simulator. All figures represent average values.

Soils	Total runoff (in.)	22.5 min. runoff rate (in./hr.)	22.5 min. infiltration rate (in./hr.)	Wash erosion (tons/acre)	Splash erosion (tons/acre)	Water stable aggregates < 0.10 mm (%)	Dispersion ratio	Silt* and clay (%)	Bulk density (g/cc)	Pores drained by 60 cm water tension (%)**	Air perm. at field capacity (μ^2)
Webster	1.42	3.40	0.52	0.83	6.50	19.3	7.37	53.0	1.25	6.48	1.35
Shelby	1.64	3.65	0.22	0.52	5.97	20.2	10.27	44.3	1.29	5.86	2.46
Clarion	1.36	3.32	0.69	0.67	4.47	21.2	14.13	32.0	1.55	3.52	2.96
Grundy	1.76	4.05	0.11	0.88	6.18	26.8	15.32	65.5	1.26	3.09	2.14
Marshall	1.75	3.90	0.14	1.20	5.79	40.5	16.58	57.4	1.40	2.90	1.97
Ida	1.50	3.58	0.43	0.55	3.80	56.5	30.02	35.1	1.32	3.32	2.66
Monona	1.76	3.99	0.13	0.90	5.68	44.8	18.42	49.8	1.37	1.67	1.42
Thurman	0.18	0.62	3.54	0.03	9.47	--	18.78	6.0	1.59	22.41	2.95

* $\leqq$ 0.02 mm.

** Per cent by volume. Cores taken from 2.5 to 3.5 inch depth. Soil for other laboratory analyses taken from surface 0.5 to 1 inch depth.

22.5-minute infiltration rates and also a large percentage of pores drained at 60 cm.

Stability of the immediate surface is an important property of the soil affecting infiltration and erosion. The percentage water stable aggregates < 0.10 mm may be a good indication of how open the soil surface will be for infiltration and resistance to erosion. The Clarion, Shelby, and Webster soils had a low percentage of water stable aggregates < 0.10 mm, had relatively high infiltration rates, and were intermediate in wash erosion. Those soils which had lower percentages of water stable aggregates < 0.10 mm usually had higher percentages of aggregates > 2.0 mm. Correlation data (Table 11) show a significant negative relationship between the per cent water stable aggregates > 2 mm vs. splash erosion or vs. wash erosion.

Soils of this study with 40 per cent or more water stable aggregates < 0.10 mm were, in general, the soils which had the most wash erosion. Surface sealing, or a tight, compact surface, was observed after rainfall for the Marshall and Monona soils. Air permeability measurements at 1 and 2 hour intervals after rainfall was terminated confirmed this observation for the soils mentioned. Air permeability measurement 24 hours later might have shown surface sealing effects better when more pores would have been drained.

The size of the primary particles at the soil surface is another factor affecting infiltration and erosion. In general, the greater the sand percentage, the higher the infiltration rate, and the lower the runoff and wash erosion. This is well illustrated by the Thurman sand, with 94 per cent sand > 0.02 mm, an infiltration rate of 3.54 inches per hour, and only 0.03 tons per acre of wash erosion. The Monona, Marshall, and Grundy, each having 50 per cent or more of silt and clay, had the lowest infiltration rates and highest runoff and wash erosion.

The dispersion ratio is a measure of the ease with which the silt and clay particles of the soil are dispersed or go into suspension. If the percentage of silt and clay is very small, a high dispersion ratio has little meaning. For example, the Thurman with a dispersion ratio of 18.78 and a total of 6.0 per cent silt and clay, would still have only a very small amount of material in suspension. In this study, soils having a dispersion ratio greater than 15 and having 49.8 per cent or more of silt and clay, were the soils (Grundy, Marshall, and Monona) which had the most wash erosion.

Wash erosion as determined by the method described in this report appears from the data to be a better measure of evaluating natural erosion by water than splash erosion or the two combined. Splash erosion would appear to be a possible field method of evaluating the aggregate stability of soil under natural conditions. A high splash erosion value indicates that the soil is easily detachable, but this does not necessarily mean that all the soil detached will be removed. For instance, the Thurman soil with the highest splash erosion had the lowest wash erosion. The reason for this is, of course, that the detached particles were heavy and total runoff was low. Where there is sufficient runoff, a high splash erosion is usually associated with a high wash erosion.

Correlations

The correlation studies of data obtained in this investigation have shown that the infiltration rate is associated with the larger pore spaces which are open at field capacities. This is indicated by the highly significant correlations* of initial and 22.5-minute infiltration rate with percentage pore space drained at 60 cm, 100 cm, and 1/3 atmosphere water tension values (Table 11). Air permeability measurements in the field may be of some value in predicting infiltration, as shown by the significant correlations of the 22.5-minute infiltration rate with air permeability at field capacity and 60 minutes after rainfall. The air permeability measurements are a reflection of the larger pore spaces open for water, as are the pore spaces at the lower water tensions. The dispersion ratio and percentage water stable aggregates greater than 2 mm showed no significant relation to the 22.5-minute—that is, the stable infiltration rate. There was a highly significant decrease in runoff, wash erosion, and the per cent water retained at 0 cm water tension as bulk density increased.

During field infiltration determinations, it was not always possible to obtain the rainfall rate desired, and when the rate exceeded the limit of 4.0 inches per hour $\pm$ 10 per cent the measurement was completed in the regular manner. The data that differed from 4.0 inches per hour by 10 per cent or more were used when rainfall intensity was compared with some other measurement. Rainfall extremes varied from 3.13 to 5.74 inches per hour for the Marshall with the extremes of the other soils falling between these limits. Whenever rainfall intensity was in excess of the infiltration rate of the soil, runoff resulted. Wash erosion, which is closely related to runoff, showed a highly significant correlation with the rate of rainfall for all the soils studied. The maximum runoff rate tended to increase with increased rainfall intensity for all soils studied as shown by the significant positive correlation.

Splash erosion decreased significantly with an increase in percentage of water stable aggregates greater than 2 mm and increased with rainfall intensity. Wash erosion decreased significantly with an increase in percentage of water stable aggregates greater than 2 mm and increased highly significantly with rainfall intensity.

Erosion Factors and Relative Erodibility of Soils

Browning's Erosion Factors

In the introduction it was indicated that one of the objectives of this research was to obtain the Browning erosion factors for the soils studied. Much of Browning's work on erosion factors, although presented before the Soil Science Society of America (in Cincinnati, 1947), has not been published. Therefore a treatment of the factors is presented here which includes, in particular, the factor due to soil type. The treatment is analytical and gives an equation comprising all the factors. For an

*Correlations are positive unless otherwise stated.

alternate treatment and for certain numerical results cited below, see Thompson (69, pp. 432-436). In brief, the erosion factors are a set of values, depending on several recognized aspects of erosion, which when multiplied together and the product then multiplied by a constant value (presently the number ten) gives the erosion in tons per acre per year. Many of the erosion factors as presently listed are tentative (see for example Ready References for Conservation Farm Planning, a loose leaf publication of the U.S.D.A., S.C.S., Milwaukee, Wisconsin, 1956) and erosion factors in a number of cases do not exist at all. Work like the present is intended to aid in establishing the factors.

The factors stem from an equation, due to Zingg (75), given by Browning *et al*. (10) in the form

$$L = \left[A/(PC)\right]^{5/3} S^{-7/3}$$

but which may also be written in the form

$$A = PCL^{0.6}S^{1.4} \tag{1}$$

where

A = amount of soil eroded (tons per acre per year);
P = practices constant. P = 1 for rows up and down hill; P = 0.50 for contour cultivation; P = 0.25 for strip cropping; and (see reference 69, Table 131) P = 0.15 for terracing.
C = constant depending on soil type (the item of principal interest in this report), crop rotation, degree of erosion, and soil treatment. The constant C will depend also on the weather of a particular region. Erosion data, however, indicate (69, p. 436) that the weather effect may be considered constant over a large part of the humid region of the United States.
S = slope of land in degrees.

Let T be a soil type factor, R a rotation factor, E a degree of erosion factor, and F a fertility practices factor. Then, assuming that C is proportional to each of these factors one may write

$$C = TREF$$

and equation 1 becomes

$$A = PTREFL^{0.6}S^{1.4} \tag{2}$$

Let now subscript s denote standard conditions for the factors in equation 2; then it becomes

$$A_s = P_s T_s R_s E_s F_s L_s^{0.6} S_s^{1.4} \tag{3}$$

and division of equation 2 by equation 3 and solution of the result for A yields

$$A = A_s \cdot \frac{P}{P_s} \cdot \frac{T}{T_s} \cdot \frac{R}{R_s} \cdot \frac{E}{E_s} \cdot \frac{F}{F_s} \cdot \left(\frac{L}{L_s}\right)^{0.6} \cdot \left(\frac{S}{S_s}\right)^{1.4} \tag{4}$$

The last seven factors in the right hand side of equation 4 (including the exponents with the last two) may be called erosion factors. Notice that when one of the numerators in equation 4 becomes equal to the standard value in the denominator, the corresponding erosion factor becomes equal to unity.

Browning et al. (10) give standard values which may be used in equation 4 as follows: A_s = 10 tons per acre per year; P_s = 1 (up and down hill corn); T_s = 1 (for Marshall type soils, among which are included Castana, Judson, Muscatine, Napier, Tama, and Waukesha); R_s = 1 (for a corn-oats-meadow rotation); E_s = 1 (for a moderately eroded soil, that is, a soil with 25 to 50 per cent of the surface soil removed); and F_s = 1 (for medium fertility, manure occasionally, and some crop residues returned); L_s = 72.6 feet; and S_s = 9 degrees. Putting these values in equation 4 yields

$$A = 10 \cdot P \cdot T \cdot R \cdot E \cdot F \cdot (L/72.6)^{0.6} \cdot (S/9)^{1.4} \ . \qquad (5)$$

The last seven factors in the right hand side of equation 5 are known as the Browning erosion factors. Tables for them are given by Thompson as his tables 131, 129, 127, 128, 130, 126, and 127, respectively. Notice that the soil type factor as given by Thompson in his Table 127 is somewhat different from that given by Browning et al. in 1946 (10, Table 2) in that Thompson associates soil type characteristics with the erosion factor T rather than with the actual soil type names. Notice also that the rotation factors as originally given by Browning et al. (10, Table 2) are approximately the reciprocal of the values as presently used (Thompson's Table 127). The rotation factor for the rotation of the present research (corn-corn-oats-meadow) is, incidentally, 1.4. The factor 10 in equation 5 etc. has, in 1956, been modified on the basis of 12 years data in addition to 10 years of data on which the factor 10 was based, to 8 (tons per acre per year). See the Ready Reference Manual referred to above equation 1.

Determination of Erosion Factors for Soil Types of Investigation

In the present work all factors but the soil type in equation 2 have been taken constant. Therefore, to determine the relative erodibility factor (T/T_s) due to soil type in equation 4, one needs only to compare the erosion of the different soil types. If the Marshall is considered the standard soil, then the soil type factors may be considered Browning factors. Nevertheless, in the following the factors are called relative soil erosion factors, since they were obtained in a manner different from that considered by Browning.

From the data obtained with the rainfall simulator the soils studied were grouped statistically for wash erosion, splash erosion, and total erosion. The group containing the most soils which did not differ statistically was used as a guide for establishing the range in tons per acre of erosion for a particular soil group. The mean erosion and variance were calculated for this group, and these were used to obtain a confidence interval at the 5 per cent level. The difference between the confidence limits obtained was taken as the group range. This value was

Table 14. Relative soil erosion factor for soils studied computed from wash erosion data obtained with the rainfall simulator. Compare Table 5.

	Wash erosion group				
	I	II	III	IV	V
Soil group	Thurman	Shelby, Ida, Clarion	Clarion, Webster, Grundy, Monona	Marshall	-
Wash erosion range (tons/acre) for soil group	<0.25	0.25-0.63	0.63-1.01	1.01-1.39	>1.39
Average wash erosion (tons/acre) for soil group	0.03	0.58	0.82	1.20	-
Relative soil erosion factor for soil group	<0.21	0.21-0.53	0.53-0.84	0.84-1.16	>1.16

Table 15. Relative soil erosion factor for soils studied computed from splash erosion data obtained with the rainfall simulator. Compare Table 5.

	Splash erosion group				
	I	II	III	IV	V
Soil group	-	Ida, Clarion	Monona, Marshall, Shelby, Grundy, Webster	Thurman	-
Splash erosion range (tons/acre) for soil group	<2.54	2.54-4.86	4.86-7.18	7.18-9.50	>9.50
Average splash erosion (tons/acre) for soil group	-	4.14	6.02	9.47	-
Relative soil erosion factor for soil group	<0.42	0.42-0.81	0.81-1.19	1.19-1.58	>1.58

used to establish groups on either side of the group for which the confidence limits were calculated. Ranges of 0.38 tons per acre for wash erosion and 2.32 tons per acre of splash erosion were established by this method.

The relative soil erosion factor for wash erosion was computed as the ratio between wash erosion of the Marshall and that of the soil, or mean of soils, being compared. The relative soil erosion factor for the splash erosion data was computed as the ratio between the mean splash erosion for the group which contained the Marshall and the splash erosion for the soil or group of soils being compared.

Relative soil erosion factors for the wash erosion data are given in Table 14. Five groups of wash erosion were set up which varied, by the established increments of 0.38 tons per acre, from < 0.25 tons per acre to > 1.39 tons per acre. The wash erosion of the soils studied ranged from 0.03 tons per acre for the Thurman to 1.20 tons per acre for the Marshall with all the soils falling in the first four wash erosion groups. Further studies may indicate the necessity of establishing one or more groups above 1.39 tons per acre of wash erosion. The relative soil erosion factor varied from < 0.21 to > 1.16 for the wash erosion groups.

Five groups of splash erosion were established, which varied by the established increments of 2.32 tons per acre, from < 2.54 tons per acre to > 9.50 tons per acre. Splash erosion of the soils studied ranged from 4.14 tons per acre for the Ida-Clarion group to 9.47 tons per acre for the Thurman with all soils falling in splash erosion groups II, III, and IV. Future investigations may indicate the need to reduce or increase the number of splash erosion groups. The relative erosion factor varied from < 0.42 to > 1.58 for the splash erosion groups established. The smaller the relative soil erosion factor, the lower is the erodibility of the soil. For both wash and splash erosion, groups were set up which were not occupied by any soils in this study. Additional study is necessary to determine the total number of groups which should be established for all Iowa soils.

The erosion data obtained with the rainfall simulator are, strictly speaking, not comparable with the data used by Browning et al. (10) because of different physical conditions for the two sets of data. Data obtained by the rainfall-simulator infiltrometer as used in this study were influenced or affected mainly by a surface layer a few inches thick or less, as the runoff and erosion measurements were made over a relatively short time.

Data of Browning et al. (10) were obtained on runoff control plots for the Fayette, Shelby, and Marshall soils, and they estimated comparative soil losses of other important soil types in Iowa by "using other physical and chemical information relating these soils to other soils." Their data were also based on total annual precipitation and runoff for an 8 per cent slope and were affected by the seasonal variations and crop cover in addition to effect of the entire soil profile. Other factors which may help account for the differences (seen below) in the two sets of data are initial soil moisture content, length of determination, soil variation, kinetic energy of raindrops upon impact, method of measurement, quantity and intensity of rainfall. The slower rate of rainfall

under natural conditions during much of the year would probably allow more water to enter the soil over a longer period of time. Under these conditions the subsoil might become the limiting factor if its conductivity was less than the infiltration rate of the surface layer of soil.

The wash erosion data obtained with the rainfall simulator show the Marshall soil to be more erodible than the Shelby. However, splash erosion data indicate that they are about equally erodible. The rotation-soil factors reported by Browning et al. (10) indicated that the Shelby soil was considerably more erodible than the Marshall. Based on the dispersion ratio and the percentage silt and clay < 0.02 mm, it can be seen that the Marshall (Table 12) had a higher content of finer material in the surface inch which can be dispersed. As a result of this higher content of fine material, there were fewer large pores drained at 60 cm, which in turn would tend to cause a higher runoff rate. The Marshall did have about 0.1 inch more runoff from two inches of rain than the Shelby. In addition, the lower dispersion ratio, higher percentage of water stable aggregates and lower percentage of silt and clay < 0.02 mm for the Shelby indicate that there was less fine material to be washed off the Shelby. There may also have been considerable variation of soil characteristics from one location to another.

Results of other studies indicate that differences may be expected between infiltration measurements made by different methods on the soil.

Musgrave and Free (49) used cylinder type infiltrometers with a 6 mm head of water to compare the effect of depth of cultivation on infiltration. They found, on the initial run with a 4-inch depth of cultivation, that at the end of 30 minutes, the Shelby had an infiltration rate of 2.16 inches per hour compared to 0.72 inch per hour for the Marshall. The wet-run 48 hours later showed an infiltration rate of 0.32 inch per hour for the Shelby and 0.24 inch per hour for the Marshall at the end of 15 minutes. However, at the end of one hour on the wet-run the infiltration rate was 0.04 inch per hour for the Shelby and 0.12 inch per hour for the Marshall. By this time the subsoil was affecting the infiltration rates more than the top part of the profile. When these soils were cultivated to a depth of 6 inches, the Shelby had an infiltration rate of 1.08 inches per hour and the Marshall 1.80 inches per hour at the end of the first 30 minutes of the initial run. At the end of 45 minutes on the wet runs the infiltration rates were 0.04 inch per hour for the Shelby and 0.16 inch per hour for the Marshall. The infiltration rate obtained with the rainfall simulator at the end of 15 minutes was 0.28 inch per hour for the Shelby and 0.02 inch per hour for the Marshall. The rainfall simulator infiltration rate at the end of 15 minutes was 88 per cent of the Shelby rate and 83 per cent of the Marshall rate as reported by Musgrave and Free (49) for a wet-run and 4-inch depth of cultivation.

Musgrave (48) reported infiltration data obtained for both Marshall and Shelby on a moist soil which had been in bluegrass sod. The infiltration tubes were installed after the surface vegetation had been removed. Data obtained showed that in the first 15 minutes the infiltration rate of the Marshall silt loam exceeded the Shelby by 0.38 inch. In the first half hour the Marshall exceeded the Shelby by 0.64 inch. Over a period of 6.5 hours, the differences in water infiltration exceeded 3.76

inches. Musgrave also reported that there was from 6.8 to 7.2 times more runoff from the Shelby than the Marshall based on data for continuous corn in control plots.

Musgrave (47) reported infiltration rates for Marshall silt loam in corn plots as varying from 0.71 to 0.75 inch per hour and direct measurements with an "erosion-type" lysimeter gave a figure of 0.74 inch of water absorbed per hour. The infiltration rate for the Marshall at the end of 25 minutes obtained with the rainfall simulator was 0.14 inch per hour with a total of 0.28 inch of rain infiltrated in 30 minutes. At the site studied with the rainfall simulator, the estimated maximum rate probably would not have exceeded 0.35 inch per hour or about 48 per cent of the rate as reported by Musgrave (47).

Smith et al. (66) used Musgrave's infiltrometer to study the effect of organic matter on the infiltration capacity of Clarion loam. Measurements were made in the second year corn of a four-year rotation. The total surface inches of infiltration at the end of 30 minutes were as follows: check = 1.03 inches, 8 tons manure = 1.44 inches, and 16 tons manure = 1.84 inches.

The results obtained on the Clarion with the rainfall simulator in the present study showed an infiltration rate of 0.66 inch per hour at the end of 25 minutes with a total of 0.65 inch of water infiltrated at the end of 30 minutes. Using these data, the total infiltration for one hour could not have exceeded 0.98 inch. The Clarion of this study was known to have received manure, so that it could probably be compared to the 8 tons of manure treatment. On this basis there was 68 per cent as much infiltration by use of the rainfall-simulator infiltrometer method used in this study.

These results point out some of the differences which may be expected between infiltration measurements made by different methods. The higher infiltration results reported by Musgrave (47) on the Marshall silt loam in second year corn in control plots, of 0.71 to 0.75 inch per hour, as compared to an estimated maximum of 0.33 inch per hour by the rainfall-simulator infiltrometer, might be due to initial moisture level and soil variation due to location. Since Musgrave's results were obtained on field plots from natural rainfall, it is possible that the soil was initially dryer than for the rainfall simulator method. The differences between the infiltration results of Smith et al. (66) on the Clarion loam and those by the rainfall simulator could be due to the differences in the method of application and initial soil moisture. The falling drops tend to both compact the surface by force and disperse the aggregates into smaller particles which plug the pores. Free et al. (29) have stated that the production of turbid water by the rainfall simulator method was one of the most important factors causing the infiltration rates determined by the "rainfall-simulator" method to be lower than those determined by the tube method.

It has been previously mentioned that erosion data obtained by the rainfall simulator are largely a function of the behavior of the surface soil and not of the soil profile. No measurements were taken of the depth reached by the standard rain applied. However, after the rain, when the infiltration cylinders were removed, it was noted that only the Thurman was wetted by the rain through the 6-inch depth of the

infiltration cylinder. The rain did not appear to have wetted the other soils more than 2 or 3 inches deep. The effect of the soil profile could be brought about by extending the infiltration cylinder so that it penetrated or passed through the B horizon, and by applying rainfall at a lower intensity over a longer period of time.

The rating or grouping of the erodibility of the soils by the method used in this study would appear to be suitable for those times of the year when there is moderate soil moisture present and the rains are of short duration and high intensity. Under these conditions the artificial rain would not penetrate the soil deeply enough to be affected by the B horizon. Wash erosion results as obtained in this study appear suitable for evaluating the susceptibility to erosion of Iowa soils when the upper profile is drained to essentially field capacity.

Splash erosion is a measure of the stability of the soil surface to raindrop impact and is made up of material which is displaced or moved by the impact of the falling raindrops. Wash erosion is probably more comparable to erosion as it occurs in the field, since it is a measure of the soil which is carried away in suspension. Although the Thurman sand was high in splash erosion, the quantity removed as wash erosion was very small. The detached sand particles were heavier than fine soil particles, but the very low wash erosion for the Thurman was a result, primarily, of the fact that there was only a very small amount of runoff to cause wash erosion. Splash erosion might be considered as a good field measurement of aggregate stability similar to McCalla's (43) falling drop laboratory technique.

SUMMARY

Infiltration measurements were made with a new type, portable rainfall-simulator infiltrometer on eight Iowa soils under a standard set of conditions so that the soils were the only known variables involved. The soils were Clarion loam, Webster silty clay loam, Thurman loamy fine sand, Marshall silt loam, Ida silt loam, Monona silt loam, Grundy silty clay loam, and Shelby loam. All soils studied were in the fall of the oat phase of a C-C-O-M rotation.

Ten plots, 3 by 3 feet, were randomly selected within an area, 9 by 21 feet, on each soil type. The vegetation was clipped at the soil surface within each plot and removed from the area. A brass infiltration cylinder, 6 inches in diameter and 6 inches deep, was installed near the center of each plot in such a manner that the soil surface was level. A sheet metal cylinder, 18 inches in diameter and 8 inches deep, and not a part of the rainfall-infiltration equipment proper, was installed to a depth of 4 inches surrounding the infiltration cylinder. The soil area within both cylinders was scratched or cultivated to a depth of about 1/2 inch, and pre-wetted so as to be at field capacity at the time of measurement. A total of 2.00 inches of water was applied to each infiltration cylinder by the rainfall simulator at the rate of 4.0 inches per hour $\pm$ 10 per cent. Runoff was caught in a runoff trough which surrounded the infiltration cylinder and which emptied into pint milk bottles. The pint milk bottles were changed at 5-minute intervals throughout the

period of rainfall and were taken to the laboratory for gravimetric determination of the rate and amount of water and soil which ran off. Erosion was subdivided into wash erosion and splash erosion. Wash erosion was considered as the sediment removed in suspension by the runoff water, whereas splash erosion was the sediment which was moved or splashed from the infiltration cylinder by raindrop impact.

Some laboratory measurement of samples of the soils were made. The results indicated that, in general, the following factors were associated with erodible soils: 3.1 per cent or less of pore space drained at 60 cm; air permeability of $2.14\,\mu^2$ or less at field capacity; 40 per cent or more of water stable aggregates < 0.10 mm; and 50 per cent or more of silt and clay with a dispersion ratio larger than 15.

Correlations were calculated to determine relationships among some of the laboratory physical measurements and infiltration and erosion as determined by the rainfall simulator. Highly significant positive correlations were found between both the initial and minimum infiltration rate and per cent pore space drained at 60 cm, 100 cm, and 1/3 atmosphere of water tension. No significant relationship was found between the minimum infiltration rate and the following items: rainfall rate, dispersion ratio, and water stable aggregates > 2 mm. A significant positive correlation was found between the maximum runoff rate and the rate of rainfall for all soils. Highly significant negative correlations were found between bulk density and runoff, wash erosion and the per cent water retained at 0 cm water tension.

No statistically significant relation was found between the dispersion ratio and wash erosion, or splash erosion. A highly significant negative correlation was found between wash erosion and the percentage water stable aggregates > 2 mm, and a highly significant positive correlation between wash erosion and rainfall intensity.

A significant negative correlation was found between splash erosion and per cent water stable aggregates > 2 mm, and a positive correlation between splash erosion and rainfall intensity.

Based on the wash erosion rate at 22.5 minutes after the start of rainfall, the eight soils studied could be divided into the following three groups: (1) erosion rate less than 0.1 tone per acre per hour (Thurman; (2) erosion rate varying from 0.95 to 1.3 tons per acre per hour (Shelby, Ida, and Clarion soils); (3) erosion rate varying from 1.55 to 2.00 tons per acre per hour (Monona, Grundy, Webster, and Marshall soils).

Based on total wash erosion for the total one-half hour rainfall period the soils were divided into four statistically different groups. The Marshall with 1.20 tons per acre had the most wash erosion for 2.00 inches of rain and the Thurman with 0.03 tons per acre had the least. For both total erosion and splash erosion the soils could only be divided statistically into two groups, composed of Ida and Clarion as the least erodible, with the remaining soils falling into a broader group of higher erosion. The Thurman, although not significantly different from the other soils of the larger group in both splash and total erosion, was considered as a third group based on other physical factors.

An equation comprising Browning's rotation factors was derived and the relative soil erosion factors then calculated on the basis of total wash erosion and total splash erosion for the soils studied. Five erosion

groups were established for both wash and splash erosion. The soils of this study fell in four of the five groups established for wash erosion and in three of the splash erosion groups. The Thurman soil was in the highest group of splash erosion for either factor and the Marshall in the highest group of wash erosion.

The portable rainfall-simulator infiltrometer used in this study appears to afford a satisfactory method of collecting erosion data for grouping soils for susceptibility to erosion for those times of the year when there is moderate soil moisture present, and the rains are of short duration and high intensity. The wash erosion results obtained by this method appear suitable for evaluating the susceptibility to erosion of Iowa soils when the upper profile is drained to near field capacity.

APPENDIX A

DESCRIPTION OF SOILS STUDIED

The following description of soils studied is taken from the unpublished "Established and Tentative Soil Series of the United States" Soil Conservation Service, Division of Soil Survey:

CLARION SERIES

The Clarion series includes Prairie soils developed under conditions of good drainage in material derived from friable calcareous glacial till of the Mankato subage of the Wisconsin glaciation, which has a loam or sandy loam texture. They differ from the Carrington soils chiefly in the lesser depth to free carbonates and the lighter texture and slightly brighter color of the subsoil and substratum. Glacial boulders are often scattered over the surface and throughout the soil profile.

I. Soil Profile:	*Clarion loam	Range:
1. (A_1) 0-10"	Dusky brown loam which has a brownish black color when moist; fine granular structure; slightly acid reaction.	8-14"
2. (A_2) 10-18"	Brownish gray to dark yellowish brown loam, usually having infiltrations of black organic matter from above; slightly acid to neutral.	8-10"
3. (B_2) 18-26"	Moderate to light yellowish brown loam or light textured clay loam; neutral.	7-11"

*Colors according to Misc. Pub. 425, U.S.D.A.

4. (C_1) 26" +	Light yellowish brown or dusky yellow, light textured clay loam or heavy loam, with abundant yellowish white spots, streaks, and concretions of lime.	10-12"
5.	Friable calcareous glacial till, light yellowish white to pale yellow when dry. Partly decomposed rock fragments are conspicuous in this horizon.	

II. Range in characteristics: Chiefly in the depth to lime, which varies from 20 to 30 inches; the texture of the "B" horizon, which ranges from a loam to a friable clay loam and the color of the surface soil.

GRUNDY SERIES

The Grundy series are Prairie soils developed from moderately deep fine textured Peorian loess. These soils occur as associates of Haig soils on slopes that usually range from 2 to 7 per cent. They differ from the Haig soils in having thinner surface horizons and browner subsoils that usually are less mottled. They differ from the Sharpsburg soils, which are developed in somewhat deeper loess, in having more clay in the subsoil and from the Seymour series, developed in somewhat thinner loess, in having less clay in the subsoil. The clay content of the subsoils of the Grundy series ranges from 42 to 50 per cent in the zone of maximum accumulation.

I. Soil Profile: *Grundy silty clay loam	Range:
1. Dusky brown to brownish-black, fine granular light silty clay loam.	8-12"
2. Brownish-gray to dark brown silty clay loam splotched and streaked with tongues of darker colors; crushed surfaces have a brownish to dark yellowish-brown color. The upper part of the horizon usually has a fine granular structure, but with depth the granules become larger and more angular.	9-13"
3. Moderate olive-brown silty clay mottled with dark orange, strong brown and rust brown iron stains. When broken out the clods fall apart into medium blocky aggregates that are coated with a thin film of dark organic matter.	7-9"

*Colors according to Misc. Pub. 425, U.S.D.A.

4. Light olive-gray, moderate orange, pale olive and weak olive; iron stains and some black; with depth the texture becomes lighter.

II. Range in Characteristics: The vlay content in the "B" horizon varies from about 42 per cent adjacent to the Sharpsburg area to about 50 per cent in the thinner loess adjacent to the Edina area. The surface texture varies from a light silty clay loam to a silt loam. The silt loam texture is usually accompanied by a "B" borizon with a clay content toward the upper limits of the series, while the silty clay loam surface is usually found with a "B" horizon having a clay content toward the lower limits of the series.

IDA SERIES

The Ida series include Lithosolic soils developed from deep calcareous loess under the influence of a grass vegetation. They differ from the associated Monona soils in having thinner surface layers, more weakly developed "B" horizons and the presence of carbonates near and occasionally on the surface. They are distinguished from the Hamburg soils chiefly by the presence of a darker surface, a higher percentage of silt and less very fine sand in the upper 10 or 20 inches of the solum and the topography which is rolling to hilly, instead of hilly to steep.

I. Soil Profile: *Ida coarse silt loam** (Moist)	Range:
1. Weak to dark brown coarse silt loam; neutral to calcareous.	0-7"
2. Strong yellowish-brown coarse silt loam with tongues of weak brown; calcareous with some small concretions.	4-6"
3. Moderate and light yellowish-brown coarse silt loam with some very fine sand; large number of lime concretions.	4-7"
4. Light yellowish-brown coarse silt loam with some yellowish-gray; crushed surfaces have a dusky yellow color; calcareous.	15-18"
5. Light yellowish-brown silt loam with yellowish-gray and dusky yellow; some iron stains; calcareous with concretions.	18-25"

*Colors according to Misc. Pub. 425, U.S.D.A.

**Formerly recognized as Knox silt loam in western Iowa.

6. Same as above except for more contrasting mottles; calcareous.

II. Range in characteristics: The thickness and texture of the surface layers and the texture of the "B" horizon; depending largely upon the topography and the distance from the bluffs. The 2-micron clay content for the "B" horizon will vary from 10-20 per cent with a dominant range of 10-15 per cent. The profile is saturated with bases, principally calcium. The content of very fine sand is variable. May include some areas of very fine sandy loam.

MARSHALL SERIES

Marshall series are Prairie soils developed on uplands from deep, medium textured loess of Peorian age. These soils differ from Tama soils in being more highly saturated with bases, usually growing sweet-clover or alfalfa without lime. They differ from the Monona soils, which are developed in deeper loess, in having more clay in the subsoil, and from the Sharpsburg soils, developed in shallower loess, in having less clay in the subsoil. The clay content of the Marshall subsoils ranges from 27 to 35 per cent in the zone of maximum accumulation.

I. Soil Profile:	(Marshall silt loam)	Range:
1. (A_1) 0-12"	Dark brown when dry to dusky brown when moist, very friable silt loam; moderately developed fine granular or crumb structure; slightly acid or neutral in reaction.	8-14"
2. (A_3) 12-16"	Weak brown friable silt loam, moderately medium granular structure, very slightly acid to neutral. When the structure particles are crushed the soil is a dark yellowish-brown.	3-6"
3. (B_2) 18-30"	Moderate brown friable silty clay loam; moderately developed fine nuciform structure; very slightly acid to neutral in reaction. When the structure particles are crushed the soil is a moderate yellowish-brown.	10-16"
4. (B_3) 30-45"	Moderate brown friable, heavy silt loam; weakly developed blocky structure; very slightly acid to neutral in reaction, The structure	

particles crush to a light yellowish-brown. Faint low contrast mottlings may be present below depths of about 35 inches. 10-20"

5. (C) 45" + Light yellowish-brown or pale brown friable silt loam; no definite structure; neutral in reaction.

II. Range in Characteristics: Chiefly in depth of parent loess, in the lime content of the parent material, in the clay content of the subsoil and depth to mottlings. In places the parent loess is calcareous below a depth of about 8 feet. The clay content of the Marshall soils varies from about 27 per cent near the Marshall-Monona boundary to about 35 per cent near the Marshall-Sharpsburg boundary. Near the Monona soils the Marshall soils may be free of mottling to a depth of several feet. Near the Sharpsburg soil the Marshall soils usually have some mottlings below about 30 inches. The nearly level areas of Marshall soils have slightly heavier subsoils and deeper, darker colored surface soils than the gently sloping areas. The steeper slopes (over 7 per cent) in the Marshall soil areas have shallower surface soils and in places low contrast mottlings occur in the deeper subsoil.

MONONA SERIES

The Monona series includes dark-colored Prairie soils developed under a grass vegetation in material derived from deep calcareous loess. They differ from the associated Hamburg and Ida soils in that the "B" horizon shows more development and the carbonates have been leached from the surface and subsoil. They are distinguished from the Marshall soils by having more weakly developed "B" horizons. Monona soils have "B" horizons with from 20 to 27 per cent 2-micron clay, whereas for Marshall soils, the range is about 27 to 35 per cent.

I. Soil Profile: *Monona silt loam (Moist) Range:

1. Weak to dusky-brown, slightly acid silt loam. 7-9"

2. Dark-brown to dark yellowish-brown, slightly acid silt loam, slightly heavier than the surface. 6-9"

3. Dark to moderate yellowish-brown silt loam, neutral reaction.

*Colors according to Misc. Pub. 425, U.S.D.A.

4. Light yellowish-brown silt loam, low contrast mottles of strong brown and pale olive. 5-40"

5. Moderate to light yellowish-brown mildly alkaline silt loam; usually enough calcium carbonate present to effervesce when treated with dilute hydrochloric acid.

II. Range in Characteristics: The thickness of the surface layer varies from a total of 7 to 10 inches; the texture of the subsoil ranges from a coarse silt loam to a heavy silt loam; the depth to carbonates is somewhat variable, depending upon relief and degree of erosion.

SHELBY SERIES

The soils of the Shelby series include Prairie soils, which are typically developed on deeply weathered Kansan ànd Nebraskan till. They usually occur on slopes and narrow ridge crests and the parent material exposed on the slopes in many locations includes successive layers of unleached and moderately leached glacial drift modified occasionally by material slumped down from the overlying loessial deposits, which blanket the flats above the Shelby areas. Seams of secondary lime occur locally but usually at 3.5 to 4 feet below the surface. The Shelby soils differ from the Carrington soils of the Iowan drift sheet in having a thinner solum and heavier textured "B" horizon and from the Lagonda soils in that the surface horizon is thinner and the "B" horizon not so tough and heavy and yellowish-brown rather than brownish-gray or gray. The principal difference between these soils and the Lindley soils is the darker color of the surface layers. These soils have an acid reaction at all depths except for seams of secondary lime below about 40 inches.

I. Soil Profile: *Shelby loam

1. Weak brown to dusky brown loam; 6 to 8 inches thick.

2. Weak brown fine granular loam with tongues and splotches of dark yellowish-brown; 3 to 5 inches thick.

3. Moderate yellowish-brown clay loam with some fine and medium sized glacial rocks; 6 to 8 inches thick.

4. Moderate yellowish-brown gritty clay to clay loam with low contrast mottles of brownish-gray light yellowish-brown and iron stains; fragments of disintegrated glacial boulders usually granites and schists.

*Colors according to Misc. Pub. 425, U.S.D.A.

5. Moderate yellowish-brown gritty clay mottled with gray rust brown and light and dark yellowish-brown; disintegrated glacial boulders; occasionally the entire mass is a mixture of sand, gravel, and boulders held together by clay.

II. Variations: The thickness of the dark colored surface layer, which may range from 6 to 12 inches; usually depends upon the rapidity with which it is removed by erosion and on the extent to which dark sediments are accumulating from higher land. Considerable variation also arises from the differences in the character of the parent material, particularly in the proportion of coarse sand, gravel, and boulders. As stated above, some secondary lime occurs as seams or along old root channels, but usually at depths of 3.5 to 4 feet below the surface. Horizons 4 and 5 may occasionally be free of mottling.

THURMAN SERIES

Soils of the Thurman Series have developed under the influence of grass vegetation from materials composed largely of loose sand with a small admixture of silt. They have darker and more stable surface layers than occur in the soils of the Valentine series, and differ from the Dickinson soils, which have developed over more or less reworked sandy drift, in having less coherent upper subsoil layers. The transition between the different horizons is very gradual in both color and texture. There is no structure development in any part of the profile. The soils are thoroughly leached of their lime.

I. Soil Profile: *Thurman loamy fine sand

1. Dusky-brown (moist) to weak brown (dry) friable, slightly coherent loamy fine sand, from 8-14" thick.

2. Transition layer of light brownish-gray loamy fine sand; 7-12" thick.

3. Dark yellowish-brown to moderate yellowish-brown incoherent sand.

II. Range in Characteristics: The dark-colored surface soil varies in thickness in proportion to erosion by wind and water. Erosion, however, is not rapid, on virgin areas, and the soils are fairly uniform. Under poor management, the cultivated soil loses its stability and serious damage may result from wind erosion. Locally, the soils may contain a small amount of gravel.

*Colors according to Misc. Pub. 425, U.S.D.A.

WEBSTER SERIES

The Webster series includes intrazonal soils within the Prairie region, which have developed over friable glacial till, of the Mankato subage of the Wisconsin glaciation, which has a loam to sandy loam texture. The Webster series includes the imperfectly and poorly drained members of the Clarion-Storden catena of soils. Glacial pebbles, stones, and boulders occur on the surface and throughout the soil. They are distinguished from the Glencoe soils by the thinner dark-colored surface layers, the lighter texture and color of the substratum and the presence of larger amounts of sand and gravel in the subsoil and substratum.

I. Soil Profile:	*Webster silty clay loam	Range:
	1. Brownish-black (moist) to dusky brown (dry) silty clay loam, slightly acid to neutral; fine to medium granular structure.	8-12"
	2. Brownish-black (moist) silty clay loam to light clay loam, very fine angular blocky structure; slightly acid to neutral.	7-9"
	3. Medium olive gray light clay loam to heavy silty clay loam with mottles of weak olive, pale olive and light olive gray; some fine glacial material in lower part; neutral reaction.	7-10"
	4. Weak to pale olive gritty light clay loam to heavy loam mottled with shades of olive and olive gray; neutral to calcareous.	8-10"
	5. Light olive gray friable loam with mottles of pale olive, weak olive, dusky yellow and medium olive gray; calcareous; glacial fragments and spots and concretions of lime.	

II. Range in Characteristics: Surface textures range from loams to silty clays and subsoils from heavy loams to heavy clay loams. Depth to lime and the light olive gray parent material is also quite variable and the range is 20 to 35 inches.

*Colors according to Misc. Pub. 425, U.S.D.A.

APPENDIX B

The Viscosity of Air at 95 per cent Relative Humidity for Various Temperatures

Air permeability was calculated in absolute units (μ^2) by the following equation as given by Grover (33): $V/t = KA\,\Delta P/\eta$. In which V = volume (cc) of air forced into the soil in time t (sec.), ΔP is the gauge pressure of the air (dynes/cm^2) in the air chamber, η is the viscosity (poise) of the air, and A (cm.) is a constant which depends on the geometry of the air flow boundaries in the soil.

The value for A is calculated as follows:

D = inside diameter of inlet tube = 14.60 cm

H = depth of insertion of inlet tube into soil = 15.24 cm

$D/H = 0.9580$

The calculated value of D/H is used to determine the value of A/D from a graph of A/D vs. D/H (33, Fig. 4).

$A/D = 2.38$

$A = 2.38 \times 14.60$ cm

$A = 34.76$ cm

The values of ΔP for the two float sizes are as follows:

ΔP large float = 3.38 cm x 980 = 3116 dynes/cm^2

ΔP small float = 3.34 cm x 980 = 3273 dynes/cm^2

V and t were determined for each measurement and recorded.

The viscosity of the air (η) was that for 95 per cent relative humidity, as suggested by Grover (33), and was determined by compositing data from Meyer and Anderson (44, p. 160) and Buehrer (11), taking account of the range of temperatures at which measurements were made.

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A CULTURE APPARATUS SUITABLE FOR PERFORMANCE OF THE PRESUMPTIVE TEST FOR THE COLIFORM GROUP UNDER FIELD CONDITIONS[1]

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One of the important problems facing the sanitary bacteriologist is the lack of a simple, economical, and rapid method for determining the sanitary quality of water. The common practice of transporting water samples to a central assay laboratory is often fraught with danger from the standpoint of reliable reporting, because of the changes in quality of water which may occur enroute. Research results (1, 2) indicate that in unrefrigerated water, certain types of bacteria other than the coliform may proliferate to such an extent before actual sampling is done that unduly high bacterial counts are obtained. On the other hand, if rapid refrigeration of the sample is practiced, "cold shock" may kill 95 per cent of the coliform organisms (3), and very low numbers of coliform organisms are erroneously indicated in subsequent analyses.

The ideal solution to this problem would be for personnel of a complete mobile laboratory to collect the samples and to conduct valid bacteriological tests immediately. From a practical standpoint, however, the expense, time, and skilled personnel required with such a complete mobile laboratory could not be justified for routine checking of the sanitary quality of even the major water supplies of a community.

Clearly, the need still exists for an inexpensive, simple, and reliable field presumptive test for the coliform group. This field test apparatus should be such that it could be carried without difficulty or special precautions to the water collection point and used successfully by public health field workers and other qualified personnel who are not necessarily experienced bacteriologists.

It is the purpose of this paper to describe a satisfactory field presumptive test apparatus, comparing results from its use with the standard APHA presumptive test.

Materials and Methods

The essential components of this field presumptive test apparatus are:

1. Five 10 ml capacity field presumptive test lactose fermentation tubes with screw caps, each tube containing the appropriate amount of sterile dehydrated standard lactose broth medium, plus a gas collection vial, and

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2. A battery and/or line-powered portable incubator.

To prevent contamination during storage, each field presumptive test tube is packaged in a sealed polyethylene envelope under sterile conditions.

To conduct the field presumptive test, the fermentation tubes are used one at a time; as each tube is taken from its sterile envelope its cap is removed, and the tube is filled with the water sample. The cap is then replaced and tightened, and the tube is shaken to mix the powdered medium with the water sample. After the medium has dissolved, the culture tube is inverted to replace the air in the gas collection vial with water. The fermentation tube is then incubated in an upright position and is observed at intervals over a 48-hour period for the presence of gas in the gas collection vial.

Experimental

This field presumptive test (FPT) was compared with the standard APHA presumptive test for sensitivity in detecting the presence of Escherichia coli in water. In this experiment, a "water sample" was prepared which contained 5.1×10^8 viable E. coli per ml of buffered saline, as estimated by violet red bile agar plate count, or 5.5×10^8 viable E. coli per ml on tryptone glucose extract agar. Serial decimal dilutions of the standardized E. coli suspension were made and 10 ml aliquots were used to inoculate APHA standard lactose fermentation tubes, and to fill field presumptive test tubes. All tubes were then incubated at 37°C and were observed at intervals for gas formation. The results obtained are presented in Table I.

TABLE I

Decimal dilutions of E. coli suspension	Theoretical number of E. coli per tube	Gas in APHA presumptive test tubes with time in hours			Gas in FPT* tubes with time in hours			
		12	18	24	12	18	24	48
10^{-4}	500,000	4/4	4/4	4/4	4/4	4/4	4/4	4/4
10^{-5}	50,000	4/4	4/4	4/4	4/4	4/4	4/4	4/4
10^{-6}	5,000	2/4	3/4	4/4	4/4	4/4	4/4	4/4
10^{-7}	500	2/4	3/4	4/4	4/4	4/4	4/4	4/4
10^{-8}	50	0/4	4/4	4/4	4/4	4/4	4/4	4/4
10^{-9}	5	0/4	2/4	2/4	0/4	4/4	4/4	4/4
10^{-10}	0.5	0/4	0/4	0/4	0/4	3/4	3/4	3/4
$10^{-11}, 10^{-12}$	0.05-0.005	0/4	0/4	0/4	0/4	0/4	0/4	0/4

*Available from Hach Chemical Company, Ames, Iowa.

Since the tests performed with the FPT tubes to this point had been carried out with pure cultures of E. coli, it seemed desirable to check the effect of other species on the FPT when present in mixed culture with E. coli. Accordingly, an experiment was conducted in which the FPT tubes were inoculated with suspensions of E. coli alone, with a mixture consisting of three species of nonlactose fermenters and E. coli, and with a suspension of Salmonella pullorum alone. The mixed culture was made up by adding together equal volumes of heavily grown broth cultures of E. coli, Bacillus subtilis, Candida albicans, and Micrococcus rhodochrous, and making serial decimal dilutions, which were used to inoculate the FPT tubes and to conduct plate counts. Total counts on TGE agar averaged 1.6×10^8 viable organisms per ml, while E. coli counts on VRB agar averaged 7.5×10^7 viable organisms per ml. The results of this experiment are presented in Table II.

Discussion

This series of experiments serves to establish that the field presumptive test for coliform organisms is at least as reliable and sensitive as the APHA presumptive test. In addition, it has the advantage that:

1. The field presumptive test (FPT) tubes have an almost indefinite shelf life, contrasted to the one week recommended for lactose broth tubes (4). This advantage is possible because the FPT tubes contain dehydrated lactose broth medium which is stable until reconstituted with the water sample itself.

2. The FPT tube will hold exactly the 10 ml volume required for the presumptive coliform test, so no sterile calibrated pipettes are required to measure the water sample.

3. The FPT tube is flat-bottomed, so it will stand unsupported, unlike ordinary culture tubes which require a rack or other holder during incubation.

4. The inoculum is not diluted with the FPT method, which is a recognized advantage in obtaining growth of small numbers of bacteria.

5. The fermentation of lactose by coliforms is an anaerobic process which is facilitated by exclusion of oxygen by the screw-cap closure of the FPT tube. This may account in part for the greater speed of the FPT tube in showing a positive reaction than does the cotton-plugged standard lactose broth tube.

6. Since CO_2 and H_2 do not appear as gas bubbles until the medium is saturated with these gases, the FPT tube with 10 ml total volume for 10 ml water sample requires less time for appearance of visible gas bubbles than does the 30 ml volume of inoculum plus medium in the standard lactose broth tube.

TABLE II

Decimal dilutions of E. coli suspension	Theoretical number of *E. coli* per tube	Gas in FPT tubes with time in hours			Decimal dilutions of mixed culture suspension	Theoretical number of *E. coli* per tube	Theoretical number of other species per tube	Gas in FPT tubes with time in hours		
		14	18	41				14	18	41
10^{-8}	32	5/5	5/5	5/5	10^{-8}	8	20	5/5	5/5	5/5
10^{-9}	3	5/5	5/5	5/5	10^{-9}	0.8	2.0	4/5	5/5	5/5
10^{-10}	0.3	2/5	4/5	5/5	10^{-10}	0.08	0.2	3/5	3/5	3/5
10^{-11}	0.03	3/5	3/5	4/5	10^{-11}	0.008	0.02	0/5	0/5	2/5
10^{-12}	0.003	0/5	0/5	0/5	10^{-12}	0.0008	0.002	0/5	0/5	0/5
S. pullorum										
10^{-3}		0/5	0/5	0/5						

All cultures used were 10 days old.

7. The FPT tubes are economical enough that they may be considered disposable.

8. Coliform organisms will survive much better suspended in culture medium than in plain water (5, 6), so collection of samples in FPT tubes, even without incubation, is superior to collection of water in sample bottles, from the standpoint of good bacteriological techniques.

The higher indicated numbers of organisms from the broth culture dilution series than from plate counts, especially with old cultures, is understandable from the standpoint of the more optimal conditions afforded by liquid medium over solid media, as has been reported in the literature for many types of organisms.

The presence of other species of nonlactose fermenting types does not seem to affect the sensitivity of the FPT in detecting E. coli as indicated in Table II.

Use of the FPT tubes should greatly facilitate the sanitary testing of municipal water supplies and should extend the range of bacteriological quality control to include home and camp water supplies. Under conditions where even portable incubators are unavailable or too cumbersome, the FPT tubes could be filled with the water sample and incubated satisfactorily in a pocket next to the body.

Summary

A modification of the APHA presumptive test for coliforms is described which has the advantages of (1) indefinite shelf life for the culture medium, (2) shorter time for obtaining a positive test, (3) containing 10 ml of water, so that pipettes are not required, and (4) compactness. All these features make the field presumptive test (FPT) tube very useful for the routine testing of the sanitary quality of water, under a wide range of conditions, particularly when a complete bacteriological laboratory is not close at hand.

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RESPONSES OF SOME MINNOWS TO FLOOD AND DROUGHT CONDITIONS IN AN INTERMITTENT STREAM[1]

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Introduction

In general, streams provide a less stable environment for fish and other aquatic life than lakes, because of the greater water level fluctuation. Intermittent streams provide an extreme example of unstable water levels since during some seasons most of the stream bed may be dry. Squaw Creek, selected for the present study, probably provides a more precarious habitat than the intermittent streams studied by Gersbacher (1937), Stehr and Branson (1938), and Gerking (1950). In these other streams there were relatively permanent pools and considerable areas of gravel. In Squaw Creek shifting sand fills the pools and the stream channel may be in different portions of the stream bed after each high water period. From 1953 to 1956, Squaw Creek was subjected to some of the worst drought conditions in years, and yet some fish survived to repopulate the stream.

Description of the Area

Squaw Creek (Fig. 1), part of the Skunk River drainage system in central Iowa, is approximately 40 miles long and has a drainage area of 210 square miles (Crawford, 1942). Squaw Creek is a very unstable stream with the bed composed mainly of shifting sands. Some silt-covered areas exist temporarily in Squaw Creek, but these areas are either scoured out by shifting sands during high water periods, or are covered by shifting sands during regular and low water periods. There are a few rubble or riffle areas but these comprise a very small portion of the stream bed.

Flood and drought conditions occur almost every year on Squaw Creek. Floods normally occur in the spring of the year but may also occur during the summer or fall months following periods of unusually heavy rainfall.

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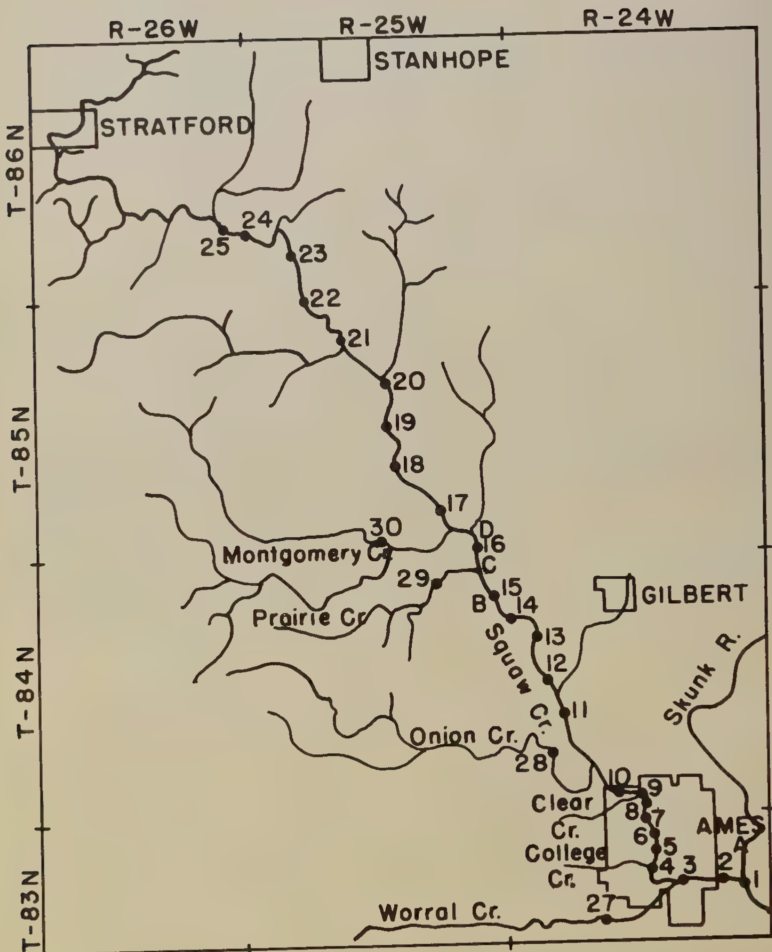

Figure 1. Stations studied on Squaw Creek, 1953-56.

In 1953 and 1955 severe drought conditions were experienced on Squaw Creek. The stream bed was dry for many miles except for occasional isolated pools. The stream was reduced to isolated pools from July, 1953 to February, 1954, and from October 5, 1955 to February, 1956. This study was initiated in October, 1953, about the middle of the 1953 drought period. There was no continuous flow when the water was below the 19-inch mark on the gauge at Station 8. When the water was over 55 inches on this gauge, it was arbitrarily called a high-water stage.

In 1954 high water periods occurred from April 30 to May 17, May 22 to May 29, June 10 to June 29, and August 23 to August 31. In 1955 high water periods occurred from June 15 to June 21, and July 14 to July 19. In the May 22-29 and August 23-31, 1954 periods the stream overflowed the banks.

Methods and Materials

The fish population of the stream was sampled with a 20-foot common sense minnow seine. It was desired to establish the average number of fish collected per seine haul as an index to the abundance of the species comprising the population. All seine hauls were made downstream for approximately 20 feet. All fish caught in the seine were counted, identified, and returned to the stream. Several factors other than numbers of fish present in the area have an effect on the catch per seine haul and some of these were evaluated (Paloumpis, 1955).

Two types of wire traps (as described by Starrett, 1948, and Carlander, 1954) were used to study the migrations of fish into Squaw Creek from the Skunk River.

An electric shocker was used to collect fish from areas not readily accessible to seining. A Briggs and Stratton 4-cycle gasoline engine equipped with a generator capable of generating 150 volts A. C. was used. The electric shock appeared to have some harmful effects upon some of the fish stunned. Fish which did not recover from the shocking were examined superficially and in all cases signs of ruptured blood vessels near the surface of the body were evident. The fish that did not survive may have come in direct contact with the electrodes.

Rotenone was also used in the stream to obtain estimates on the relative abundance of the species in the fish population. The average length of stream to be treated was approximately 100 yards. Block seines were placed at each end of the stream to prevent fish from entering or escaping from the area to be sampled. A handful of powdered rotenone was first placed in a bucket of water and mixed until a fairly homogeneous suspension was obtained. This suspension of powdered rotenone in water was introduced at the upstream end of the sampling area and was carried downstream by the current. All fish were collected as they appeared at the surface of the water. After fish in distress failed to appear at the surface of the water, the lower stop seine was raised and the dead fish caught by the stop seine were removed.

The Fish Population

During the three-year period, the following species of fishes were collected from Squaw Creek:

1. Quillback, Carpoides cyprinus. Fairly common in deeper pools.
2. Highfin sucker, C. velifer. Only 2 specimens from a flood plain pond.
3. Northern hog sucker, Hypentelium nigricans. Only 2 specimens.
4. White sucker, Catostomus commersoni commersoni. Not common, but fairly abundant during spawning season when it runs up from the Skunk River.
5. Carp, Cyprinus carpio. Common.
6. Western golden shiner, Notemigonus chrysoleucas auratus. Only 2 specimens from a flood plain pond.
7. Creek chub, Semotilus atromaculatus atromaculatus. One of most important species in the creek.
8. Silver chub, Hybopsis storeriana. Only in a few collections following high water.
9. Hornyhead chub, Hybopsis biguttata. Only occasional specimens.
10. Plains suckermouth minnow, Phenacobius mirabilis. Only from swift waters.
11. Emerald shiner, Notropis atherinoides atherinoides. Uncommon.
12. Northern common shiner, N. cornutus frontalis. Common.
13. Bigmouth shiner, N. dorsalis dorsalis. The most abundant species.
14. Red shiner, N. lutrensis lutrensis. Second most abundant species.
15. Sand shiner, N. deliciosus. Rare.
16. Brassy minnow, Hybognathus hankinsoni. Not common.
17. Bluntnose minnow. Pimephales notatus. Not common.
18. Fathead minnow, P. promelas promelas. Common.
19. Stoneroller, Campostoma anomalum pullum. Not common.
20. Channel catfish, Ictalurus punctatus. Uncommon.
21. Black bullhead, Ameiurus melas. Abundant in some flood plain ponds.
22. Stonecat. Noturus flavus. Collected at only one riffle area.
23. Smallmouth bass, Micropterus dolomieui dolomieui. One small specimen.
24. Largemouth bass, M. salmoides salmoides. A few small specimens, perhaps from stocking.
25. Green sunfish, Lepomis cyanellus. Common in deeper holes.
26. Bluegills, L. macrochirus macrochirus. A few specimens, probably stocked from farm ponds.
27. Orangespotted sunfish, L. humilis. Fairly common in deeper holes.
28. White crappie, Pomoxis annularis. A few specimens.
29. Johnny darter, Etheostoma nigrum nigrum. Only from riffle areas.

Table 1. Percentage of seine hauls in which each species of fish was taken for all stations, Squaw Creek, September, 1954 to March, 1956.

	Sept. 1954	Nov. 1954	Mar. 1955	Apr. 1955	May 1955	June 1955	July 1955	Aug. 1955	Oct. 1955	Mar. 1956
Number of hauls	25	44	17	60	11	246	246	201	6	55
Bigmouth shiner	80	91	94	95	82	98	94	98	100	44
Red shiner	52	36	12	72	64	81	81	67	100	5
Common shiner	12	16	18	37	27	36	27	25	67	0
Emerald shiner	56	62	0	18	27	8	5	4	0	0
Bluntnose minnow	0	25	29	50	55	45	67	81	100	7
Fathead minnow	0	11	6	50	45	35	57	41	83	0
Creek chub	88	50	41	32	27	34	23	19	100	5
Brassy minnow	24	20	24	40	73	30	27	16	50	0
Stoneroller	12	11	0	12	27	8	11	25	83	0
Suckermouth minnow	4	0	12	8	18	0.5	2	0	0	0
White sucker	16	9	6	10	18	8	12	3	33	0
Quillback	20	57	35	12	27	3	7	5	33	0
Johnny darter	24	7	12	2	18	6	9	22	33	0

As would be expected with the extreme variations in the stream habitat from season to season, the relative and absolute abundance of the various species varied at different times in the study. Some of these differences are shown by the percentage of seine hauls containing each species (Table 1). These percentages are related to the abundance of the various species since the probability of capture in a seine haul is increased as the abundance of a species increases. However, the percentages are more closely related to the degree to which the species is spread throughout the sampled area. The average catch per seine haul (Table 2) is perhaps a better measure of abundance. For this comparison only the data from Stations 8-10 are included since all other stations were not equally sampled in each of the sampling periods. The difference between the two measures of abundance is most strikingly illustrated in the comparison of the bigmouth and red shiners. Both species were taken in the majority of the seine hauls (Table 1) but the catch of bigmouth shiners was usually over 50 per haul while that of red shiners was usually less than 5.

The fish appear to be more abundant during low water and drought stages, September, 1954 to March, 1955 and August to October, 1955, than during normal water levels. However, it should be remembered that the habitat was much reduced and that the fish populations were therefore concentrated. A higher proportion of the total population was taken with each seine haul at low water than at high water levels. Undoubtedly the total population in Squaw Creek was much lower in drought periods than during normal water conditions.

Some of the effects of the floods and droughts can be best understood by considering a few of the species separately.

Table 2. Mean catch per seine-haul at stations 8-10, Squaw Creek, September 1954 to March, 1956.

	Sept. 1954	Nov. 1954	Mar. 1955	Apr. 1955	May 1955	June 1955	1-10 July 1955	10-31 July 1955	Aug. 1955	Oct. 1955	Mar. 1956
Number of hauls	25	36	17	18	5	78	42	44	76	6	20
Bigmouth shiner	49	76	71	48	46	23	54	40	112	201	2
Red shiner	2	1	1	4	7	3	2.5	3	3	123	0
Common shiner	0.1	0.3	0	0.7	0.4	0.3	0.7	0.2	0.5	4	0
Emerald shiner	7	4	0	0.5	0.2	0	0	0.1	0.05	0	0
Bluntnose minnow	0	0.3	0.4	11	9	1.1	5	2	7	36	0
Fathead minnow	0	0.2	0.06	2	0.4	0.6	6	4	5	19	0
Creek chub	8	12	4.6	1.4	0.8	1	1.1	0.5	1.2	27	0
Brassy minnow	0.4	2	0.6	0.8	1.6	0.4	0.7	0.4	0.3	10	0
Stoneroller	0.3	0.1	0	0.2	0.4	0.2	0.3	0.3	3	20	0
Suckermouth minnow	0.4	0	0.2	0.8	0	0	0.02	0.1	0	0	0
White sucker	0.3	0.05	0.06	0.3	0.8	0.1	0.2	0.2	0.05	1	0
Quillback	1	5	0.5	0.5	0.4	0.06	0	0.1	0.05	4	0
Johnny darter	0	0.4	0.4	0	0.4	0.2	0.03	0.2	0.7	1	0

Carp

Carp were more abundant in the Skunk River and bordering ponds than in Squaw Creek. They were collected, however, from deep holes with brush and debris in Squaw Creek. The first collections from Squaw Creek came after the second high water period in the spring of 1954. Young-of-the-year carp (1.0 inches total length) were collected from the smaller streams tributary to Squaw Creek on June 2, 1954, 11 days after the onset of the second high water period. Seine hauls and trap catches in Squaw Creek after the high water period had receded contained large numbers of carp. The carp may have spawned in the ponds bordering Squaw Creek prior to the onset of the high water period and migrated into the Creek when the ponds and creek were connected by the overflow.

Table 3. Age determinations of scale samples from carp collected from pond C on November 20, 1954 and from Squaw Creek in August, September, and October, 1954.

Total length in inches	Pond C: Number of fish in age class 0	Pond C: I	Squaw Creek: Number of fish in age class 0	Squaw Creek: I	Squaw Creek: II
2.0 - 2.9	1		1		
3.0 - 3.9	8		15		
4.0 - 4.9	25		4		
5.0 - 5.9	24	8	1	2	
6.0 - 6.9	19	29		8	
7.0 - 7.9		40		4	
8.0 - 8.9		20		6	
9.0 - 9.9		12		2	1
10.0 - 10.9		3			1
11.0 - 11.9					1

Scale samples for age determinations were taken from carp collected in pond C on November 20, 1954 and from Squaw Creek in August, September, and October, 1954 (Table 3). Of the scales taken from 231 carp collected in pond C, 193 exhibited a band of slow growth at the edge of the scale. This slow growth may have been the result of crowding as the pond decreased in size during the fall months and as the fish approached the carrying capacity of the pond. A similar band of slow growth was present on 16 of the 45 carp examined from the creek proper.

Adverse conditions affected a greater percentage of the fish in the pond than in the creek. In the creek the population was not as definitely fixed as in the pond since the fish are able to move in and out of areas. Possibly the carp in the stream moved from habitats which were becoming unsuitable.

Creek Chub

Creek chubs, 5.0 inches total length and less, were collected from varied habitats in Squaw Creek and small streams drained by Squaw Creek, but the larger creek chubs inhabited the deeper waters.

The creek chubs have an upstream breeding migration in the spring of the year. The upstream migration in 1954 and 1955 began during the last week of March. All creek chubs collected in the traps at the start of the upstream migration were males and in the middle of April the creek chubs collected in the traps were predominantly females. Spent female creek chubs were collected in the traps in the last week of April, 1955, at which time the water temperature ranged from 58 to 60°F.

Low water levels create a barrier to the upstream movements of fish (Larimore, 1952) and the delay in the re-establishment of a continuous flow of water delayed the 1956 spring migration of fish into Squaw Creek. On April 15, 1956 adult creek chubs were observed concentrating at Station 1 in the Skunk River. The gonads of creek chubs collected at Station 7 on June 2, 1956, shortly after the stream flow made connection with Skunk River indicated that the creek chubs had not yet spawned. Temperature is usually considered as the important factor regulating the spawning time of fishes. The presence of unspawned creek chubs this late in the year indicates that suitable habitat may also be an important factor regulating spawning time. Fabricius (1950) reported that while temperature was an important stimulus to spawning of pike, Esox lucius, absence of suitable aquatic plants would delay spawning.

In 1954 a flood occurred on April 30 to May 17, shortly after the first creek chubs had spawned in Squaw Creek. On May 12, seine hauls in feeder creeks emptying into Squaw Creek contained many young creek chubs. Apparently some creek chubs spawned in these tributaries which stabilized much faster after the high water period than did Squaw Creek.

Emerald Shiner

The emerald shiner population was quite high in September, 1954, the year that the water level was not greatly reduced in Squaw Creek. From that time on, however, the emerald shiner population decreased and none were collected after August, 1955. Apparently this species could not stand the restricted habitat and the concentration of fish in isolated pools.

Northern Common Shiner

In Squaw Creek the northern common shiner inhabited clear water areas with rubble bottom. The northern common shiner was more abundant in the Skunk River than in Squaw Creek and was not collected in the smaller tributaries or pools bordering Squaw Creek. The numbers of common shiners collected in the seine hauls were never large (Table 2) but the wire traps took many common shiners in the spring.

Trapping data in the spring of 1954 did not indicate much upstream migration, but the 1955 data suggest a considerable migration with a

peak on April 15. Raney (1940) reported that the upstream migration of common shiners in some localities in New York appeared to be from the deeper pools where they had wintered.

In Squaw Creek the common shiner spawns from the middle of April until the last of May. Spent female common shiners were first collected in the traps on April 17, 1954 and on April 20, 1955.

Bigmouth Shiner

The bigmouth shiner was the most abundant species of fish in Squaw Creek. The bigmouth shiner is a pioneer species in the smaller streams and is capable of adapting to the changing habitat conditions experienced in unstable streams (Starrett, 1948).

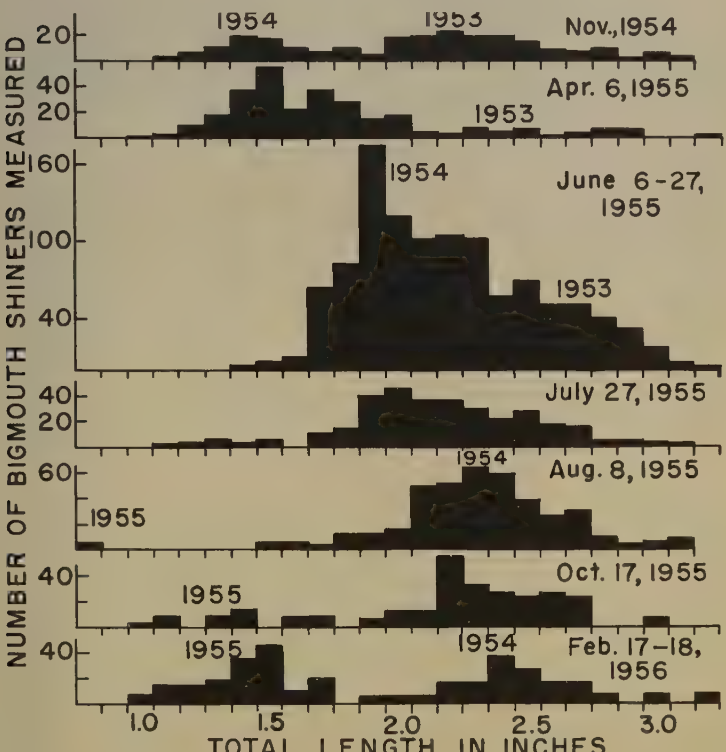

Figure 2. Length-frequency distribution of the central bigmouth shiner, Squaw Creek, November, 1954 to February, 1956.

The bigmouth shiner spawns in Squaw Creek in the middle of July. Length-frequency distributions indicate that bigmouth shiners attain an average length of 1.4 inches by the end of the first year and an average length of 2.4 inches by the end of the second year (Fig. 2). No bigmouth shiners over 3.2 inches were collected. Age determinations of scale samples substantiated the length-freqnency data and indicated that the shiners have a two-year life span. All fish 2.0 inches and less, total length, collected during the period June 6-27, 1955 had no annuli on their scales. They probably represent the 1954 year class since it was too early for them to be young-of-the-year fish. It was therefore assumed that the annulus would be formed a little later. All fish over 2.3 inches had scales with single annuli and belonged to the 1953 year class (Table 4).

Table 4. Age determinations of scales of bigmouth shiner, Squaw Creek, June 6-7, 1955.

Total length in inches	Number of fish in age class* I	II
1.4	3	
1.5	3	
1.6	11	
1.7	23	
1.8	32	
1.9	21	
2.0	14	8
2.1	5	5
2.2	5	11
2.3		8
2.4		7
2.5		5
2.6		2
2.7		3
2.8		2
2.9		1

*It is assumed that the fish had not yet formed annuli, since the fish listed as age class I showed no annuli and certainly were not young-of-the-year.

The bigmouth shiner was the most abundant and most widely distributed species throughout the period of the study. The differences in catch per unit effort (Table 2) are probably largely caused by differences in water levels and do not reflect any major changes in abundance of this species except for the March, 1956 seine hauls which reveal a great drop in the population during the winter of 1955-56.

Starrett (1951) found that the most abundant species of fish in the Des Moines River, Iowa, were the late spawners and attributed their success to the fact that high water stages normally occur in May and June. The occurrence of high water periods later in the summer might affect the late spawners. In Squaw Creek the bigmouth shiner was a late spawner but the occurrence of a high water period in 1954 during the spawning period of this species apparently did not affect its abundance.

Red Shiner

The red shiner occurred in 71.8 per cent of all seine hauls but comprised only 5.88 per cent of the total catch, which indicated that the species had a wide habitat range but was not especially abundant. They were collected in large numbers in December, 1953 and October, 1955, when Squaw Creek was composed of isolated pools. At those times it comprised a greater proportion of the total catch than normally. Apparently this species is able to tolerate crowding with better success than does even the bigmouth shiner.

Bluntnose Minnow

The bluntnose minnow was found to inhabit areas with sandy bottom and clear water and was more abundant in the tributary streams than in Squaw Creek. No specimens were collected in 1953 nor in 1954 until July 13. It is probable that the flood period of June 10 to 29 brought them out of a tributary stream or pond.

The bluntnose minnow is reported to spawn over an extended period from late May to late August (Hankinson, 1919; Van Cleave and Markus, 1929; Hubbs and Cooper, 1938; and Westman, 1938). Small bluntnose minnows were collected in seines in July, August, and September, indicating that spawning continued much of the summer in Squaw Creek.

Fathead Minnow

The fathead minnow was collected from areas where the water was muddy and the flow of current was not too great. Habitat of this type occurs sparsely and only on a temporary basis in Squaw Creek. The fathead minnow was more abundant in the flood plain ponds C and D than in Squaw Creek. Ponds C and D had silt bottoms and were more suitable habitat for the fathead minnow than the unstable conditions in Squaw Creek.

Small young-of-the-year fathead minnows were collected in seine hauls in June, July, and August, which indicated an extended spawning season. Wascko and Clark (1951) ar 1 Wynne-Edwards (1932) reported the breeding season of the fathead minnow extended from May 1 through August. Markus (1934) observed that one female fathead minnow deposited eggs on the same nest on 12 different occasions from May 16 to July 23.

Length-frequency distributions of 1698 fathead minnows collected from pond C on November 21, 1954 suggested that the population was

composed of one age class (Fig. 3). Age determination of scale samples collected from these fish indicated the population was composed of two age classes. The fish less than 2.4 inches total length belonged to age class 0 and the few fish over 2.5 inches belonged to age class I. The extended spawning period which results in successive recruitment of young-of-the-year fish and the high mortality rate among adult fish following the spring spawning period (Markus, 1934) probably contributed to the appearance of only one age class in the population sampled.

The fathead minnow was fairly common throughout the study period. The increase in the population of fathead minnows in July, 1955, was probably due to the appearance of young-of-the-year fish in the seine hauls.

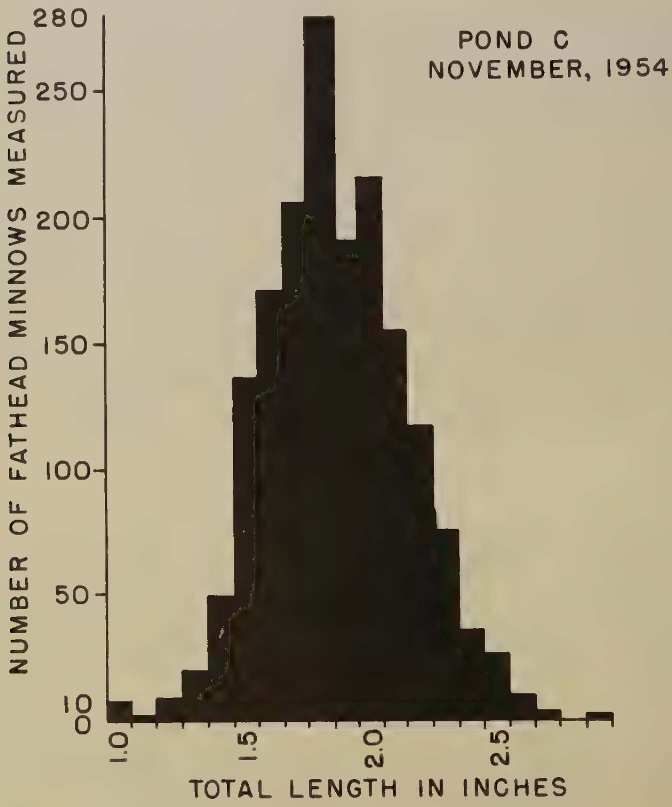

Figure 3. Length-frequency distribution of fathead minnows collected from pond C, November 20, 1954.

Stream Havens

The instability of the water level in Squaw Creek was an important factor limiting the survival of aquatic life in most of the stream. Reduced water levels resulted in the exposure of productive areas to drying and the concentration of fish in the remaining water areas. Sudden rises in water levels displaced adult and young-of-the-year fish, destroyed the spawn and reduced the available food supply of the fish. The floods and drought resulted in rather frequent reductions of the total fish population.

The survival of a fish population in Squaw Creek is possible only because certain rather limited habitats remain even during the most severe catastrophes which overtake the stream as a whole. These habitats may be referred to as "stream havens" (Paloumpis, 1956).

During flood periods the small tributary streams may serve as stream havens. During the drought periods, the isolated pools in the channel, the bordering ponds and the Skunk River serve as important stream havens. These stream havens were not always safe and the fish in them were subjected to the dangers of concentration, predation, and suffocation.

In the 1953-54 and 1955-56 winters the dissolved oxygen in several of the isolated pools was completely used up and the fish suffocated. In some of the other pools the ice froze to the bottom. But there were still a few pools in which fish survived.

The importance of Skunk River as a haven and as a source of fish for repopulation of Squaw Creek following severe drought and winter conditions was shown in the spring of 1956. In March, 55 seine hauls revealed the presence of only 4 species: bigmouth shiner, red shiner, bluntnose minnow, and creek chub, and none of them was numerous. Stream flow did not increase enough to provide a connection with the Skunk River until May 13, 1956. On June 2nd, 13 species of fish were found in an approximately 100-yard section of Squaw Creek.

Summary

1. Squaw Creek, located in central Iowa, is an intermittent stream which experiences flood and drought conditions almost every year. The Squaw Creek bed is predominantly shifting sand which results in an unstable and unproductive habitat. During drought periods, the creek is reduced to a series of isolated pools.

2. From October, 1955 to June, 1956, fish were collected from Squaw Creek by seines, wire traps, electric shocker, and rotenone. These observations covered two drought years, 1953 and 1955, and one year of floods, 1954.

3. The populations of most species of fishes in Squaw Creek are not large. Only the bigmouth shiner appears to be abundant. Most of the species have been successful in maintaining themselves regardless of the drastic changes which occur in the habitat. The fish population changes seem to be rather small compared to observed habitat changes.

4. Carp, bluntnose minnows, and fathead minnows seem to be maintained largely by flood plain ponds. These ponds probably also provided the few black bullheads and sunfishes taken from the creek.

5. Creek chubs, stonerollers, common shiners, and the suckers are probably maintained largely by migrations from Skunk River.

6. There was some evidence that the red shiner was capable of withstanding crowding in isolated pools even better than the bigmouth shiner. The emerald shiner practically disappeared as the stream became a series of isolated pools.

7. The fish population in Squaw Creek is able to survive drought and flood periods largely in certain areas or stream havens. During flood periods, small tributary streams probably serve as havens. During drought, isolated pools in the channel, flood plain ponds, and the Skunk River are the important havens.

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MOVEMENTS OF CHANNEL CATFISH IN DES MOINES RIVER, BOONE COUNTY, IOWA[1]

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Abstract

Although stocked channel catfish, Ictalarus punctatus (Rafinesque). have traveled many miles downstream, most studies have indicated little movement of channel catfish tagged and released at their point of capture. Metal strap tags were placed on the opercles of 3077 channel catfish in a 7-mile stretch of the Des Moines River. Only 7 returns, of 86 where the location was reported by anglers, came from outside the 7-mile area, 2 upstream and 5 downstream. Electric shocking and netting, on the other hand, indicate that the channel catfish do not long remain in the same pool. Differences in size distributions and in rates of recapture indicate a greater susceptibility of adult catfish to capture in hoop nets during the spawning season than later in the year. In estimating abundance or size distribution in a population by netting this seasonal difference in catchability must be considered. The spring tagged fish contributed more to the angler's catch than did summer tagged catfish, perhaps due to the size difference. Tag returns indicate a minimum annual angler harvest of 4.6 per cent of the catchable-sized fish.

Introduction

Past investigations have revealed striking differences in the movements of tagged channel catfish in rivers. Wickliff (1934) obtained 14 returns from 682 channel catfish stocked in Ohio streams. One fish was recaptured at the point of release and the remaining 13 fish had traveled 5 to 100 miles with a definite downstream migration. Seaman (1948) obtained distances from release to recapture up to 239 miles for channel catfish stocked in Mud River and Middle Island Creek in West Virginia. He reported a predominantly downstream migration with an occasional upstream migration. Only two fish from a total of 98 had moved less than 9 miles. These two studies indicate a considerable downstream movement of stocked catfish.

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In contrast, tagged catfish released at or near their point of capture show much less movement. Harrison (1953) found that in the Des Moines River, Iowa, of 101 tags recovered, only 33 channel catfish had moved from the area where tagged and released, and of these, 15 had traveled no more than one mile. Twenty-four fish which had been tagged one to five years previously were recaptured in the original area of marking. The majority of this information was collected from fish tagged and recaptured in fishway traps at dams. McCammon (1956) found that channel catfish tagged in December 1953 in Colorado River, California, showed practically no movement between time of tagging and recapture, while recovery data from those fish tagged in April and May 1954, demonstrated that some fish move considerable distances. Although McCammon did not find a definite pattern of migration there was a tendency for fish to move downstream from the Palo Verde Weir area, particularly after the first three months following their release. This downstream movement may be evidence, in part, of a seasonal migration pattern in which fish move upstream during the spring and early summer months and downstream during the fall and winter.

The greater movement of the stocked catfish is probably a response to their being placed into a habitat strange to them. Furthermore the more favorable sites in the habitat may already be occupied by resident fish. The present study, dealing with native fish, indicates that although the movements are rather restricted, there may be seasonal differences in the distribution and activity of channel catfish.

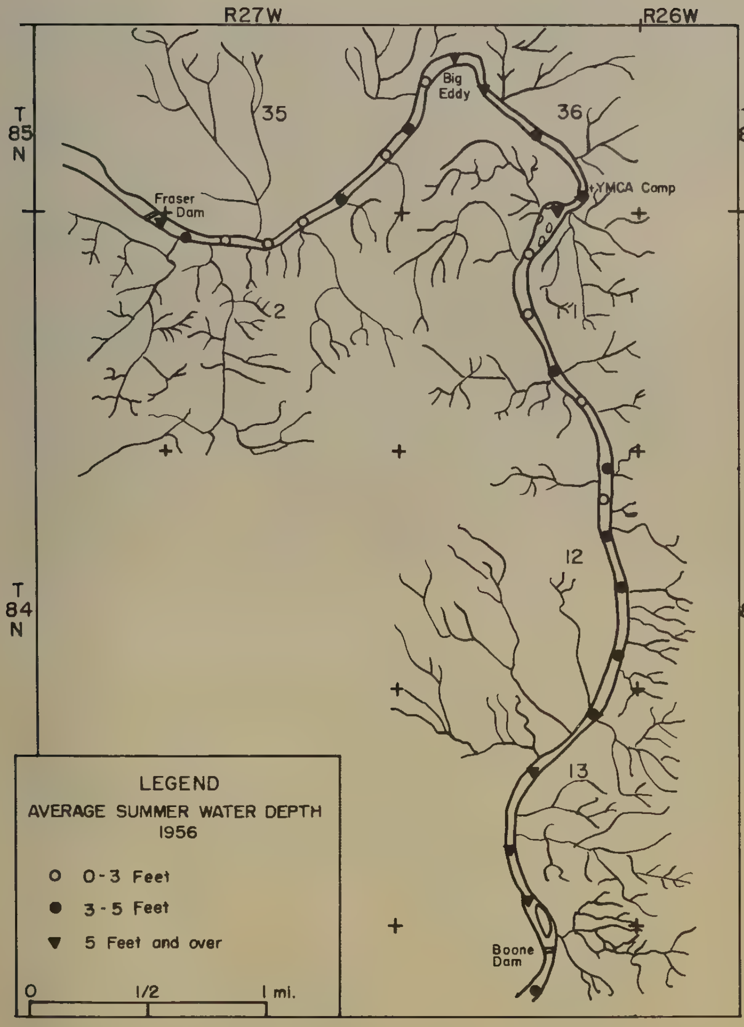
Description of Study Area

A portion of the Des Moines River (R 27W, T 85N, Sections 35 and 36; R 27W, T 84N, Sections 1, 12 and 13) was chosen for intensive study. Lowhead dams, 6 to 8 feet in height, are located at both ends of the study area, but cause very little increase in stream width. The stream bottom was composed chiefly of sand-gravel or sand-silt with rubble and boulders in a few areas. Water depths in the study area are indicated in Fig. 1; in addition, small holes existed at boulders and brush piles, where the increased current had a digging action. Water depths can and do change rapidly as a result of increased water currents scouring out areas with deposition in other areas.

Water stages in 1955 and 1956 recorded at a permanent recording station in the study area were far below average readings of previous years. Effects of these low-water stages on the movement data are not known. Movement over the lowhead dam at the upper end of the study area was undoubtedly more difficult than at normal or higher water stages.

Methods and Materials

In the 7-mile section of the Des Moines River in 1955 and 1956 tags were placed on 3077 channel catfish caught by hoop nets, wire traps, or electric shocker. Most of the tags were placed on fish in a 2-mile stretch near the upper end of the 7-mile area. The principal tagging


R27W
R26W
T 85 N
T 85 N
T 84 N
T 84 N
35
36
2
1
4
12
13
Big Eddy
Fraser Dam
YMCA Camp
Boone Dam
LEGEND
AVERAGE SUMMER WATER DEPTH 1956
0-3 Feet
3-5 Feet
5 Feet and over
0
1/2
1 mi.

method was a monel metal strap tag placed on the opercular bone, but a limited number of fish (62) were marked by a streamer-type tag applied behind the dorsal spine (Joeris, 1953). The streamer-type tag was discontinued after recaptured fish showed signs of the tag cutting through the flesh; in addition, none of the fish tagged with this tag were recaptured more than 20 days after being released. Examination of all captured catfish revealed only 10 fish with marks on the operculum indicating loss of strap tags. Several channel catfish with tag intact have now been taken two years after tagging.

Season Shift in Size Distribution

The size distribution of hoop-net and wire trap catches was not uniform throughout the entire tagging season (Fig. 2) which indicates that only segments of the population were being sampled during the study period. A much larger proportion of the catch during April to June was composed of fish over 12 inches long than in the catch the rest of the season. Similar differences in size distribution of catch have been reported by Harrison (1955), McCammon (1956), and Kelley (1953). Changes in effectiveness of hoop nets for large fish could cause this difference (Muncy, 1957). It was shown that a ripe fish in a hoop net increased the catch during the spawning season. Another explanation could be a wider dispersal of adult fish or a reduction in their movements following the spawning season, June to July.

Tag Returns

During both 1955 and 1956, the percentage of recaptures in hoop-net catches increased in early spring, reached a peak during spawning season, and then decreased rapidly (Fig. 3). If a stable population were being sampled, the percentage of recaptures in the catch should increase with cumulated numbers of tagged fish.

No pattern of movement by tagged channel catfish was found in hoop-net recapture data. Fish tagged from the same net catch were frequently recaptured later on the same date at hoop nets located both upstream and downstream from the original tagging site. Channel catfish recaptured more than once exhibited the same irregular pattern of upstream and downstream movements.

Repeated electric shocking in two sections (1 and 36) of the study area failed to yield repeated recapture of channel catfish previously marked from electric shocker catches. Only three fish in Section 36 and seven fish in Section 1 were captured after being tagged from previous electric shocker catches (Table 1). Tagged fish were not recaptured twice by electric shocking in either section. Failure to obtain repeated recaptures may have indicated ineffectiveness of electric shocking rather than the absence of the tagged fish in sections. In general, channel catfish which were large enough to be tagged were not taken by the electric shocking randomly distributed over the entire river, but they were obtained in greatest numbers from under and around cover. This cover

Table 1. Channel catfish catches by electric shocking in two sections of Des Moines River, Iowa, listing recaptures from previous tagging.

Section and date	Total	Over 6.5"	Cumulated number tagged in section	Total recaptures	Fish tagged from previous electric shocker catches: No.	Location in comparison to release	Interval (days)
Section 36							
9/9/55	52	20		0			
9/14/55	57	16	20	1			
10/11/55	2	1	36	0			
6/13/56	4	4	37	1	1	up 0.2 mile	273
6/18/56	14	12	37	1			
7/30/56	79	59	40	2			
9/8/56	7	6	85	1			
9/22/56	37	28	91	1	1	0.0 mile	54
10/6/56	104	76	112	0			
11/3/56	54	43	134	4	1	up 0.8 mile	56
11/17/56	0	0	134	0			
Section 1							
6/11/56	3	3		1			
6/16/56	9	9		3			
6/23/56	9	9	6	2			
7/16/56	19	19	13	2			
7/23/56	25	24	25	1			
7/25/56	24	21	49	0			
8/2/56	6	6	66	1			
8/3/56	64	51	71	3			
8/15/56	22	12	107	1			
9/12/56	141	125	118	3	1	down 0.1 mile	51
9/29/56	142	115	212	8	4	up 0.1 mile	66
						0.0 mile	17
						down 0.1 mile	17
						down 0.5 mile	17
10/20/56	77	44	291	3	2	up 0.3 mile	21
						0.0 mile	96

Table 2. Location and time interval of angler returns from tagged channel catfish for 1955 and 1956, Des Moines River, Iowa.

	Recaptured 1955		Recaptured 1956			
	Tagged 1955		Tagged 1955		Tagged 1956	
Capture location	No. fish	Time interval in days	No. fish	Time interval in days	No. fish	Time interval in days
0-0.5 mile of tagging	9	4-105	3	387-410	12	19-116
Upstream						
0.5-2 miles	5	10-51	-	-	6	12-105
2-3 miles	9	10-64	1	316	8	18-60
Over 3 miles	-	-	-	-	2	20-40
Downstream						
0.5-2 miles	4	19-50	-	-	6	97-138
2-4 miles	3	22-29	2	316-424	11	14-150
Over 4 miles	2	61-67	-	-	3	52-58
Unknown	-		1	-	5	-
Total	32		7		53	

preference of channel catfish made possible concentrated effort at such places. If tagged fish remained at the location of capture or similar areas, then more recaptures should have been taken than indicated in Table 1.

Since electric shocking and netting were limited to certain sections of the study area, angler returns gave a much broader coverage of fish movements (Table 2). Data from angler tag returns may give biased results. Returns are not complete for all fish angled; and anglers tend to be selective toward the larger fish. Recapture records for tagged channel catfish demonstrate that accessibility of fishing places on the river influenced the location of angler returns. Favorite fishing places at deep holes or lowhead dams produced 67 of the 79 known tag returns and locations in the 7-mile study area.

Only seven known recaptures were obtained from outside the study area (Table 2). Two tagged channel catfish were able to pass over Fraser Dam, a lowhead dam located three miles above the main tagging area, despite the fact that there had been no high water stages. These fish were captured 8.5 and 10 miles above the dam. From a pool at the base of Fraser Dam, a total of 14 angler returns was obtained. This suggests a concentration of tagged fish below this structure. Five tagged

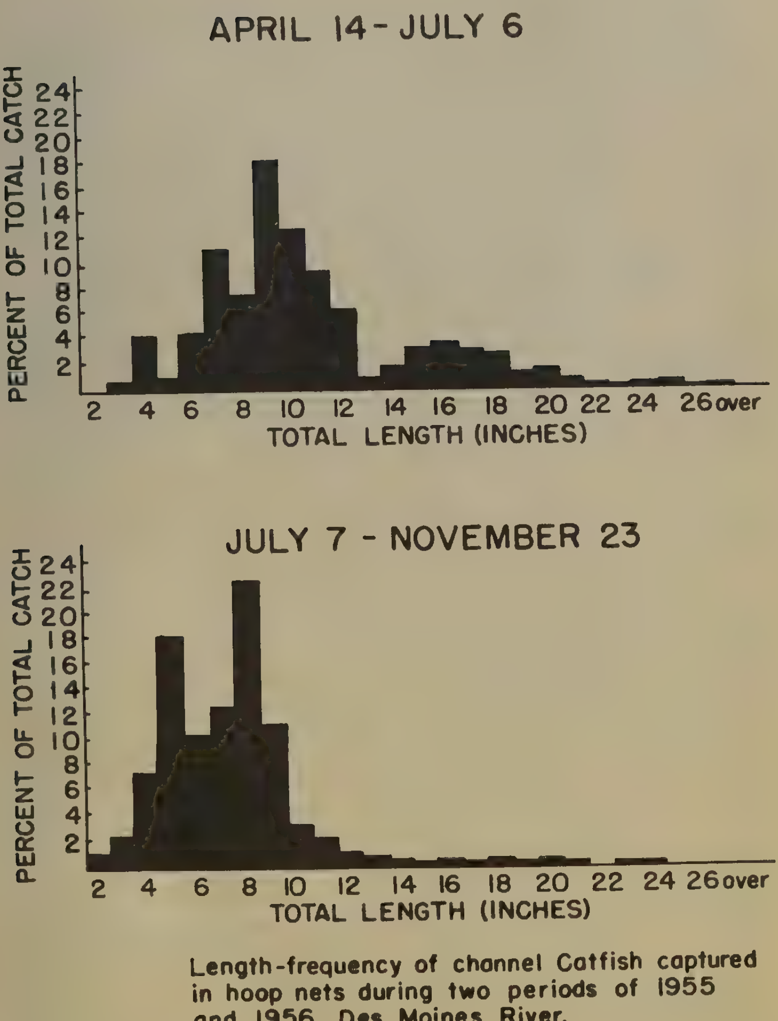


Fig. 2. Length frequency of channel catfish captured in hoop nets during two periods of 1955 and 1956, Des Moines River, Iowa.

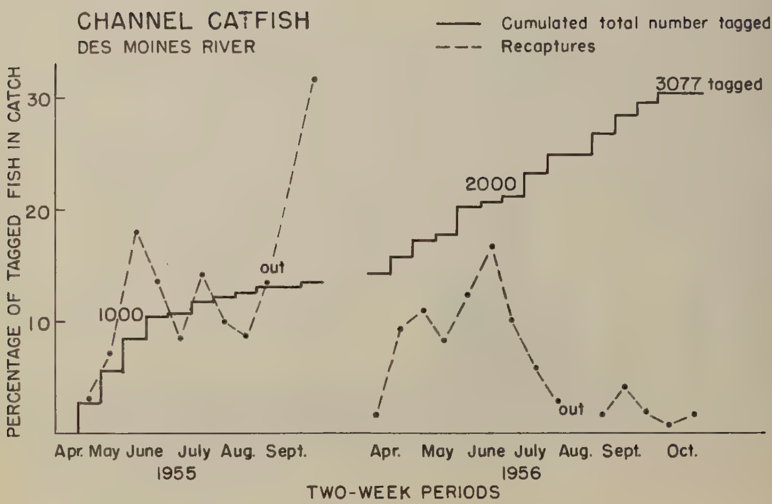


Fig. 3. Percentage of channel catfish recaptures in total trap and hoop net catches as compared to the cumulative numbers of fish tagged.

channel catfish which had passed over the Boone Water Works Dam were recaptured downstream 9, 9, 14, 24, and 26 miles from the release locations. Even though most fish were tagged within a 2-mile section of the Des Moines River, later tag returns indicate that these tagged fish had dispersed over the entire 7-mile study area.

Channel catfish tagged before and during the spawning season yielded a higher angler return and moved greater distances than fish tagged following the spawning season. Only 1.1 per cent of the channel catfish tagged from hoop-net and trap catches during the period following spawning season were caught by anglers. In comparison, 4 per cent of total fish tagged prior to and during the spawning season were represented in anglers' returns. Anglers reported only 1.4 per cent of the fish tagged from electric shocker catches. The electric shocker was used mostly in late summer, following the spawning season. McCammon (1956) noted a similar tendency for fish tagged in the fall to move less than those fish tagged in spring.

Ninety-two tag returns from fishermen represent a 3 per cent return from all channel catfish tagged in this investigation. This figure would be a minimum estimate since fishermen contacted while they were fishing in the study area reported previously catching tagged fish which were not recorded. A return of 4.6 per cent was obtained if the number of recaptures were compared to number of tagged channel catfish over 9.0 inches total length, the minimum size reported as kept by fishermen.

Discussion

Differences found during this study in the extent of movement and rates of recapture by nets and angler returns indicate changes in the movements of channel catfish following the spawning season. Any use of nets to study the abundance or size composition of channel catfish populations must therefore take into consideration these seasonal differences. Barnickol and Starrett (1951, p. 284) state "the seasonal activities and habitat preference of various fish complicate sampling with commercial gear." Other factors in addition to spawning probably cause changes in the extent of movement but no evidence was collected during this study on these factors.

As in previous studies on unstocked channel catfish, no evidence of a directional migration was obtained from recapture data. Repeated electric shocking in some release areas failed to yield continual recaptures of tagged fish. In addition, trap recaptures indicated that tagged fish did not remain in the same pools. Apparently the channel catfish forage over a considerable range and cannot be expected to remain in the same pool for long. The actual home range limits of the channel catfish are not known from this study, but probably exceed one mile in each direction.

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AUTHOR INDEX

SUBJECT INDEX